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Application of Space Technology to Crustal Dynamics and Earthquake Research

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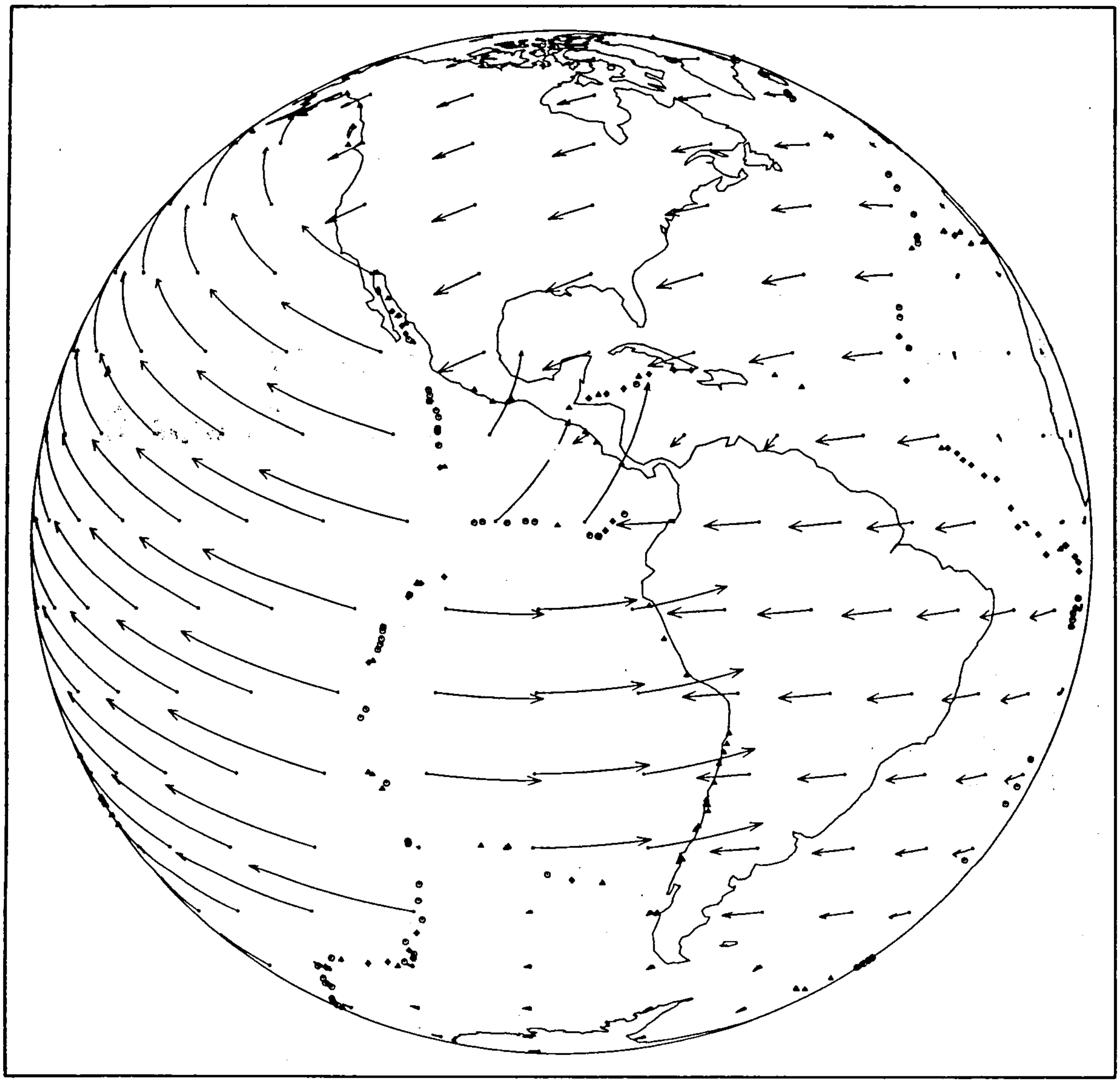

Frontispiece: Absolute plate motion with respect to a hot-spot frame of reference (Minster-Jordan Model AM1-2). Velocity vectors drawn along small circles about rotation poles; 1 cm/year maps into 2 geocentric degrees at 90° distance from the pole. For example, total convergence on the west coast of South America is about 9 cm/year. From Minster and Jordan (1979). Tandem efficaci do manus scientiae (Horace, Epodes XVII).

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NASA Technical Paper 1464

Application of Space Technology to Crustal Dynamics and Earthquake Research

Geodynamics Program Office
Resource Observation Division
NASA Office of Space and Terrestrial Applications
Washington, D.C.

NASA
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and Space Administration

Scientific and Technical Information Branch

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TABLE OF CONTENTS

SECTION 1: OVERVIEW

SECTION 2: INTRODUCTION

SECTION 3: SCIENTIFIC BACKGROUND

SECTION 4: MEASUREMENTS AND MODELS

SECTION 5: REMOTE SENSING FOR
EARTHQUAKE HAZARD ASSESSMENT/REDUCTION
AND FOR RESEARCH IN GEODYNAMICS

SECTION 6: IMPLEMENTATION

APPENDICES

LIST OF FIGURES

SECTION 3: SCIENTIFIC BACKGROUND

SECTION 4: MEASUREMENTS AND MODELS

SECTION 5: REMOTE SENSING

SECTION 6: IMPLEMENTATION

LIST OF TABLES

PREFACE

This document describes an extensive program of crustal dynamics studies in the 1980's to be undertaken cooperatively by several U.S. Federal Government agencies and by the governments of other countries. The program evolved from the development, over the past decade, of technology to apply space methods to basic problems in geodesy and geophysics. A significant practical aspect of the program is its potential contribution to understanding the processes that cause earthquakes, and eventually to the alleviation of earthquake hazards.

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SECTION 1

OVERVIEW

1.1 INTRODUCTION

This document describes the NASA research and applications program in crustal dynamics for the period 1980-1990. The goal of this program is to apply space methods and technology to advance scientific understanding of earth dynamics. The plan extends and carries forward the existing NASA programs in geodesy and geophysics and focuses them on two specific objectives: first, to support the U.S. national program in earthquake hazard reduction by studying dynamic processes related to earthquakes; and second, to support the ongoing national and international program of research in global geodynamics. In order to establish the context in which the NASA activities will be carried out, we start by summarizing the objectives of these broader programs.

1.2 EARTHQUAKE HAZARD REDUCTION PROGRAM

The NASA Geodynamics Program has been structured to support the national program authorized by the Earthquake Hazard Reduction Act of 1977. Under this act Congress initiated a broad research program whose goal is to save lives and property by developing the capability to predict earthquakes (and possibly eventually to control them). Primary responsibility for the program lies with the U.S. Geological Survey and the National Science Foundation, but other agencies are expected to continue their activities relevant to the program.

The National Earthquake Hazard Reduction Program is aimed toward a comprehensive understanding of the dynamic processes that produce earthquakes. The practical objective is a prediction system based on well-understood physical principles so that reliable estimates can be made of the time, place, and magnitude of earthquakes. However, it is recognized that a basic understanding of tectonic processes will be required before the practical objective is likely to be achieved.

In order to implement a practical earthquake prediction system, two fundamental requirements must be met. First, our knowledge of the physical causes of earthquakes must be improved and extended. There are many aspects of this problem, involving research in several areas of geology and geophysics. These are crustal dynamics, earthquake mechanisms, the properties of rock-forming materials at high temperatures and pressures, and the petrological and geochemical processes related to crustal dynamics.

The second requirement for a practical earthquake prediction system is to solve the very difficult social, engineering, economic, and political problems involving the impact of earthquakes (and earthquake predictions) on society. These include the analysis of seismic risk for land use planning and earthquake hazard insurance, establishment of reasonable building codes for earthquake-resistant structures, and assessment of the impact of earthquake predictions on civil activities. The last of these involves planning and policy decisions at every level of federal, state, and local government.

It is not difficult to identify NASA's proper role in the research program necessary to achieve the objectives of the National Earthquake Hazard Reduction Program. The reasoning developed in this document is that NASA has unique capabilities to contribute to the research aspects of the program, primarily in the areas of crustal dynamics and gravity field measurement. It will be seen that space technology has unique capabilities to make accurate, timely observations of land movement on a large scale and that such observations are potentially very important in understanding the dynamic processes that produce earthquakes. Also, gravity field measurements from space give important information on a global basis concerning the driving forces of plate tectonics motions (for a review, see Vogel, 1979).

1.3 GLOBAL GEODYNAMICS

The emerging new science of geodynamics combines aspects of geology, geophysics, and geochemistry (Drake, 1976). A loosely organized international research program in geodynamics has grown up in the last twenty years mainly as a result of the formulation of the plate tectonics model of dynamic processes. International coordination is the responsibility of the Interunion Commission on Geodynamics (ICG) of the International Council of Scientific Unions (ICSU), whose present activities are embodied in the International Geodynamics

Project. This project, begun in 1970, is aimed at the coordination and encouragement of individual research programs in many countries. Its objectives are to study four major problems in geodynamics (National Academy of Sciences, 1973):

1. The physics of the earth's interior, its properties and behavior, and the sources of energy for movements within it;

2. Understanding of crustal movements in seismically active areas, and their relationship to recent structural history;

3. Understanding of evidence for paleodynamic movements, whose record is preserved in orogenic belts;

4. Understanding of the (mainly vertical) movements, past and present, that occur within more stable areas.

1.4 NASA's ROLE: APPLICATION OF SPACE TECHNOLOGY TO EARTH DYNAMICS

In order to identify more precisely what NASA's role should be in these broad programs of research in geodynamics and earthquake processes, we must start by discussing how space-related technology can be used, and how it complements other possible observational procedures. For comprehensive reviews of many aspects of space applications, see Mueller (1978).

Space techniques are diverse, giving direct and indirect measurements of many phenomena. For the direct study of crustal movements, accuracies of the order of a few centimeters per year are required, over distances of hundreds or thousands of kilometers. Classical methods are inadequate for this purpose. The modern approach is for an extraterrestrial reference point to be used, with respect to which the position of points on the earth's surface can be determined. There are two ways of doing this. The first uses laser ranging, i.e., measuring the time of flight of very short laser pulses to a reflector above the earth's surface. This requires a high-altitude satellite whose orbital position can be determined to appropriate accuracy. Lageos and the Moon are examples of retroreflector-equipped satellites in orbits high enough to be free from serious perturbations caused by effects that are difficult to model, i.e., the complex gravity field structure due to density inhomogeneities in the Earth, variations in the radiation pressure exerted by solar radiation reflected from the Earth, and variations in atmospheric drag. Knowing the satellite ephemeris, the position of a laser ranging station can be determined in an Earth center-of-mass coordinate system.

The other technique is long baseline microwave interferometry. Here the reference system is a coordinate frame fixed in distance radio sources (quasars), whose radio noise is received by two radio telescopes. By cross-correlating the two records and determining the signal delay times, the three-dimensional position difference between the two observing stations can be derived. Strictly speaking, these position differences must be referenced to the earth's center-of-mass coordinate system before they can be compared with laser ranging results or results obtained from ground-based methods. However, many quantities, such as baseline lengths or changes in relative positions, can be compared directly (for a review, see Shapiro, 1978).

Two interferometry systems are currently in use. With very long baseline interferometry (VLBI), the radio telescopes have independent clocks and recording systems, and they can be arbitrarily far apart. This is the approach being taken by NASA, the National Geodetic Survey, and other agencies. The other approach is connected-element interferometry, where the two radio telescopes are linked together by cable, and only one clock and recording system is necessary. The maximum separation between the two elements appears to be of the order of a few hundred kilometers, which precludes use of this technique for making observations of position differences over continental scale distances.

The accuracy with which position or position differences can be determined by either of the space techniques is five to ten centimeters at present, but it is expected that this will be reduced to 2-3 centimeters within the next two years as a result of refinements of technique, better satellite ephemerides and earth gravity models, and more sophisticated equipment.

Space technology is presently making important contributions to geodesy, oceanography, and geodynamics through mapping of the earth's gravity field. Study of the fine structure of the earth's gravity field can lead to inferences about the distribution of mass in the earth's interior and about the possible convection currents in the mantle that may play an important role in the movement of tectonic plates and the dynamics of plate interactions. In addition, knowledge of the gravity field is required in order to establish a datum with respect to which heights can be measured.

Space methods also contribute to understanding dynamic processes in the earth through study of the Earth's magnetic field; this is one of the mission objectives of the Magsat satellite that will be launched in 1979. Magsat will map long wavelength magnetic anomalies over both oceanic and continental areas and is also expected to give useful information on the main geomagnetic field. This is pertinent to geodynamics, since the geomagnetic field is caused by dynamic processes in the earth's core, and the interaction between the core and the mantle is involved in a complex and poorly understood way in the excitation and damping of polar motion.

To see why space techniques can make important contributions to earthquake research and to geodynamics, we must review the fundamental problems in earth dynamics and the capabilities of ground-based methods to address these problems. This discussion makes up a major part of this document and we will only summarize it here.

We take as the conceptual framework of the entire program the plate tectonics model of global tectonics. In this model, the outer part of the earth is made up of about a dozen large quasi-rigid blocks or plates (and many smaller ones) which are moving relative to one another. The plates spread apart along the worldwide ocean ridge system and in rift zones connected to it, and material from the mantle accretes onto the plates at these places. Elsewhere the plates converge, and one plate is being thrust under the other, the descending slab moving down into the mantle to be melted and recycled.

The combination of forces that drive the plates, and the way the plates deform in response to these forces, are not perfectly understood at present, and the plate-driving mechanism is one of the foremost problems in geophysics today. The NASA Geodynamics Program is aimed at shedding light on these questions.

The plate tectonics hypothesis is almost universally accepted by earth scientists today, after almost twenty years of sometimes heated debate since the basic idea was first put forward by Harry Hess, J. T. Wilson, and others. A few scientists are still unconvinced by the overwhelming body of geological and geophysical evidence that supports the plate tectonics idea (for example, see Beloussov, 1979), but their counter-arguments are not widely accepted (see Sengör and Burke, 1979). Most geologists and geophysicists accept and use the hypothesis because, as Lagrange said in a different context, "c'est une belle hypothèse, cela explique beaucoup des choses."

Still, there has yet been no direct observation of the postulated movement of the tectonic plates. Thus, one of the primary objectives of the NASA Geodynamics Program is to provide a crucial test of the plate tectonics theory by direct measurement of plate movements. Assuming that the results will agree with the theoretical predictions, this confirmation is not very exciting scientifically, for two reasons. First, it would not prove that plate tectonics is correct, since theories and hypotheses cannot be proven by observation. Second, the frontier of research in earth sciences has moved

far beyond the simple question of whether or not the plates actually move. It is by the study of the deviations from the smooth and steady motion predicted by the present theory of plate tectonics, and in the large-scale deformations of the plates, that important advances in understanding the dynamic earth will be made. Nevertheless, the philosophical impact of this key experiment will be significant.

Possibly the most fundamental problem in earth dynamics today -- and it is one which must be solved in order to understand earthquakes -- is to determine what mechanism or combination of mechanisms is causing the motion of the lithospheric plates that make up the earth's surface, and how the plates respond to these driving forces. Current hypotheses involve one or some combination of three mechanisms: coupling of the plates to convective flow in the underlying mantle, negative buoyancy of subducted slabs, and gravitational sliding down from thermally maintained topographic highs at the ocean ridges. The relative importance of these candidates is at present poorly understood.

Research on this fundamental problem involves many disciplines in geology, geochemistry, geophysics, and marine sciences. However, for our purposes we need only recognize that several important geophysical questions must be answered in order to fully understand the forces that drive the plates, the way the plates respond to these forces, and how earthquakes result from this interaction. These questions include:

1. What is the nature of the contemporary movement of the plates with respect to one another? Are the plates moving smoothly and steadily in the same direction and with the same rates as they have been doing over periods of millions of years, as determined by geological and geophysical evidence?

2. How does an individual plate move? Does it move uniformly and smoothly as a rigid body sliding over the underlying asthenosphere, or does the movement consist of episodic strain waves propagating across the plate as a result of fracture or creep events at the plate boundaries? What is the nature of the distortion and deformation of the plates, if they are not rigid, and what physical properties of the lithosphere and asthenosphere govern the distortion? What role do geological imhomogeneities such as ancient tectonic zones and zones of weakness play in determining these distortions?

3. How does the strain field near a plate boundary change with time as stresses which have accumulated due to the plate-driving forces are released in seismic or creep events at the boundaries?

4. Why are there stresses in the interiors and passive margins of plates large enough to cause isolated zones of persistent and potentially hazardous seismicity?

5. Is there any coupling between fluctuations in the earth's rotation and the occurrence of large earthquakes and other transient geodynamical phenomena? The kinetic energy of rotation of the earth is enormous compared to the total energy release through heat flow from the earth or to the total seismic energy release per year, and small but significant fluctuations in the earth's rotation rate are known to exist.

The common factor of these questions -- all of which are important to understanding the causes of earthquakes -- is that answering them involves precise determination of position or rate of change of position in three dimensions and at places separated by hundreds or thousands of kilometers. The rates of change of position expected from geophysical and seismological considerations are of the order of several centimeters per year (about the same rate that fingernails grow), implying that over reasonable time scales, observational systems must be able to detect position changes of a few centimeters.

The time scales for different geodynamic phenomena vary widely, from millions of years for the gross plate motion down to a few seconds to hours for strain release in transient creep events or earthquakes. However, ground-based instruments such as seismometers or strain meters are adequate and more suitable than space methods for keeping track of movement at the short end of this time scale. For movements that occur over longer times, experience indicates that resurvey of position at intervals of one of three months should be adequate for monitoring changes in the earth's strain field, at least at the present level of accuracy in the most active tectonic areas, and intervals of a year or more in less active regions. For studying the rheology of the asthenosphere, observations should be made daily or weekly in the epicentral region of large earthquakes. Reconnaissance measurements at intervals of six months to two years would be useful to provide information on where anomalous movements are occurring, but would be less useful in establishing the time of the movements.

1.5 WHY SPACE TECHNOLOGY IS NEEDED

The classical ground-based geodetic methods of trilateration, triangulation, and leveling are quite capable of measuring relative position and position changes to the required accuracy over short distances, but they suffer from inherent limitations when measurements must be made over distances of hundreds or thousands of kilometers, as is the case for the earthquake hazard reduction and geodynamics programs. The limitation is that observations must necessarily be made in a series of small steps, and errors inevitably accumulate in this process. Also, such surveys are expensive on a per-mile basis, and so time-consuming that they cannot be frequently repeated.

For determining plate tectonic motion and the large-scale deformation of plates, space techniques are far superior to any other approach. This also is the case for setting up geodynamic control networks around seismic zones, to which ground observations can be tied. Much improved determinations of the earth's rotation and polar motion are necessary in order to permit accurate plate tectonics measurements, as well as for understanding the geodynamical processes which affect the earth's rotation, and the necessary accuracy can only be obtained by the space techniques.

For measurements at interval distances of 20-200 kilometers within seismic zones, the optimum choice is not so clear. At the present state-of-the-art, the best horizontal geodetic surveys are accurate to about three parts in 10^7, or three centimeters in 100 kilometers. Improvements in accuracy are likely, but probably at increased cost. The best possible leveling accumulates errors at a rate of about one millimeter times the square root of the length of the traverse in kilometers, or one centimeter in 100-200 kilometers. However, geodetic leveling at this kind of precision is difficult, and the cost of releveling frequently over large networks is prohibitive. The use of gravity measurements to indicate where elevation changes may be occurring is a much cheaper alternative to leveling, but it is not yet known how frequently false alarms may occur due to causes not associated with elevation changes. It appears at present that it will be desirable to monitor elevation changes as well as gravity changes (Whitcomb, 1978).

Determination of the earth's gravity field is an area where space techniques already have contributed a great deal. Solutions for the spherical harmonic coefficients of the gravitational potential complete to degree and order 32 have been obtained by combining all available satellite and ground data, and are being used in investigations of the driving forces for plate tectonic motions, and other questions. GEOS-3 and Seasat-A altimeter data has increased our knowledge of the gravity field variations over the oceans, but leaves strong needs for further important oceanic gravity field data. Improved gravity data over land also is needed in order to understand the basic mechanisms of plate tectonics and the effect of convection in the mantle. Because of the long correlation lengths for important gravity field variations, it would be very difficult to obtain the necessary information over the more remote areas of the world by ground measurements.

We see that while on the one hand there may be little advantage to using laser ranging or VLBI methods over short distances, these methods are ideally suited to extend and complement ground-based techniques over regional distances. For distances of the order of a few tens of kilometers, it appears that space methods can also contribute. Two approaches are being studied as part of the NASA Geodynamics Program. One is to place a laser in orbit around the earth and the passive retroreflectors on the ground; the other is to use signals from the Global Positioning System satellites as VLBI sources. Other GPS-based systems are being studied by other agencies. One or both of these space-derived systems may have economic and operational advantages compared to ground-based lasers and quasar-based VLBI for determining relative position changes over the ranges of distances of about 20-100 km.

In order to derive the location of points on the earth's surface from space data, it is necessary to know the orientation of the earth. This is specified by the instantaneous pole position and universal time (UT1), both of which vary with time, as well as by adopted values of the earth's nutation and precession. These parameters can be determined simultaneously with the position coordinates, or independently, as is now done using astronomical techniques by the BIH. However, with independent determination of polar motion, the station position coordinates derived from one observational method cannot be compared with those derived from another method (even during the same time period) unless both solutions use the same polar coordinates. Thus, a proper comparison of station coordinates requires that common polar motion and UT models be used. This can be most easily accomplished by a dedicated polar motion and UT

monitoring service using space techniques, as BIH and IPMS now serve this need using classical techniques. It is also necessary that the pole position be determined to the same observational accuracy as the positioning methods. This is the objective of the NGS Polaris system, which will use fixed VLBI stations to determine polar motion (Carter and Strange, 1979).

For the measurement and comparison of intersite distances and determination of position changes with time, the requirement for accurate earth rotation models is less severe, since the baseline lengths are independent of the coordinate system used.

1.6 USE OF REMOTE SENSING DATA

Orbital remote sensing is becoming recognized as an important tool for studying geological and geophysical processes on the earth. This technique is, of course, our primary approach to studying the surfaces of other planets. Landsat images have been used to study the tectonics of remote areas, especially Central Asia and Iran (see references in Section 5). Advanced techniques are being developed or have recently been put into operation: for example, the Heat Capacity Mapping Mission was launched in mid-1978 to acquire thermal data that is expected to be useful for differentiating between rock types. Seasat returned a number of synthetic aperture radar images of land areas as well as oceans, and these are being studied together with Landsat and HCMM data for geological interpretation. Other new instruments and methods are being studied for future flights.

Exploiting space remote sensing data to its fullest capability will be an important adjunct to the crustal motion operations that are the primary thrust of the NASA program. In Section 5 we discuss the potential contributions of remote sensing techniques, and how they might be integrated into a comprehensive approach to the application of space technology to terrestrial geology and geophysics.

1.7 STRATEGY FOR NASA'S PROGRAM

There are three major components in the NASA Geodynamics Program. The first is the use of interlocking networks of fixed and transportable laser ranging and VLBI stations to acquire regional-scale and global-scale data. This information is of great importance to basic research in global geodynamics and of significant value for meeting the objectives of the Earthquake Hazard Reduction Program.

The second component is the development of improved space techniques for measuring relative positions at large numbers of points in seismic zones, which may lead to much more complete monitoring of possible crustal movements than otherwise would be feasible. The third is the measurement of the earth's gravity field with sufficient accuracy to meet the needs of both basic research in global geodynamics and applications to the important field of physical oceanography.

We summarize as follows the strategy for a program to meet NASA objectives:

Establishment of Observational Capability

Develop and validate geodetic methods for measuring the position of points on the earth's surface, the earth's rotation and polar motion, and modeling the fine structure of the earth's gravity field. This is the thrust of a major part of NASA's present programs in geodynamics.

Perform applied research and development leading to establishment of an internationally supported network of permanently operating fixed observatories to serve as benchmarks on different lithospheric plates for measurement of interplate motion and plate deformation, and to determine earth rotation and polar motion.

Develop small, highly mobile laser ranging and VLBI field systems for regional-scale strain observations.

Begin an international program of observation using both fixed sites and mobile stations, with the objective of measuring large-scale plate deformation and interplate motion.

Local and Regional Deformation

Develop and demonstrate methods for making rapid and cheap measurements of relative position in seismic zones. At present, the most promising systems for this purpose include the spaceborne laser ranging system and radio techniques using the Global Positioning System satellites.

Measure the strain field and its rate of change at selected seismically active plate boundaries, and study the relationship between these observations, other geophysical parameters, and earthquake processes.

Gravity Field

Investigate the gravity field to accuracies needed for applications to both global geodynamics studies and to oceanography.

Establish the measurement systems required for meeting these needs.

Carry out observational programs to improve knowledge of the earth's gravity field, and correlate observations with other data to study mantle convection and its role in global tectonics.

In addition to the above elements, it will also be necessary to include the following tasks:

Supporting Activities

Establish a data management system for the efficient storage, retrieval, and exchange of data between program participants within NASA, other scientists conducting geodynamics research, and between federal and international agencies.

Synthesize data to develop models for geophysical and geological processes involved in crustal dynamics and earthquake processes.

Conduct research and development to improve the space technology used in geodetic and geodynamic applications; consider applications of space technology to areas of geodynamical research that are not part of the NASA Geodynamics Program at present. An example of the latter would be precise position observations from benchmarks on the ocean floor.

1.8 PROGRAM ELEMENTS

As described herein, we plan to continue the study of the relative motion of the North American and Pacific Plates begun in 1972 (San Andreas Fault Experiment) and to address the question of plate stability (beginning in 1979) by initiating a program of long-term monitoring using fixed and mobile stations in North America, on islands in the Pacific Plate, and in Australia. For global studies of plate motion the existing and planned VLBI, lunar laser, and Moblas sites in both the US, Europe, and South America will be used; however, additional facilities will be required in Alaska, Japan, and Brazil.

Also beginning in late 1980, mobile stations will be deployed to study crustal motion and regional plate deformation in active tectonic areas of the world. These studies will involve coordination with other US agencies and cooperation with international groups. The first priority will be to establish a network of about 30 mobile sites in the western United States and Mexico to monitor crustal movements over an area extending as far as 1500 kilometers from the San Andreas Fault. These sites will be visited initially about twice a year and will require about 60% of the mobile site capability. The activities will be coordinated with programs planned by the USGS and the National Geodetic Survey (NGS). Mobile stations are self-contained for power and communications, and the only site requirements are a reasonably stable pad and several benchmarks within a few hundred meters of the pad.

Operational monitoring of the network sites in the United States will be assumed by NGS in 1983.

Mobile stations will also be used to study tectonic motions in the Caribbean region (about 20% of capability) and to establish "benchmarks" at strategic locations within a few major fault zones of the world, examples of which are the Motagua Fault in Central America, the North Anatolian Fault in Turkey, and the Alpine Fault in New Zealand. The Caribbean region is particularly important to the plate tectonics model since each type of plate boundary is present in this highly complex region. Furthermore, nearly every major city in this region has been devastated by a large earthquake within recent history. The "benchmark" studies across the major faults will provide important reference baselines in areas where large continuous motion or large earthquakes might be expected.

Beginning in 1983, in cooperation with other international groups, we propose to extend the intensive studies of regional deformation to New Zealand, the western part of South America, Alaska, and the Fiji-New Caledonia area. The scope of the crustal dynamics program will be enlarged to encompass at least three or four other interesting regions beginning in 1984, in order to study a variety of geodynamic phenomena.

The several methods for local strain studies discussed in an earlier section are currently under study. Design concept studies for a spaceborne laser ranging system will be completed in 1980. Field tests to intercompare the GPS-based radio systems now under development are planned for late 1980. Based on these tests and other analyses, a decision will be made in 1982 as to which system, if any, should be procured for operational use. An important application of these systems is to fill in the spaces between network points in the regional deformation observation program, densifying the networks from spacings of 200-500 km to spacings of 40-60 km.

To support the fixed and mobile station observations, improved measurements of polar motion and earth rotation will be provided routinely by a global network of fixed VLBI and satellite and lunar laser ranging stations. A portion of the fixed and mobile satellite laser ranging stations will be dedicated to maintaining the accuracy of the Lageos orbit determination and to support precision tracking requirements for other satellites. The Moblas laser ranging stations, which are cumbersome and not easily moved, will be used for this purpose (see Section 6-2.1).

Based on assumptions we believe are realistic, our analysis dictates a need to upgrade current facilities and to initiate procurement of additional mobile VLBI and mobile laser ranging stations in FY 80 and FY 82, respectively. Similarly, we have concluded that a second Lageos (offset in orbit by 12 hours) would be beneficial to the program, and could reduce on-station time for the mobile lasers; this satellite is included in the later years of the program.

We have also provided for the acquisition of improved gravity field data by a Gravity Field Satellite mission (Gravsat) in 1985, and for the continued monitoring of secular variations of the earth's magnetic field by a follow-on Magnetic Field Satellite Mission in 1984.

1.9 COST ESTIMATES

Estimates have been made of the costs associated with the development and use of systems required to support this Plan. This includes the use of fixed and mobile VLBI and laser ranging systems, data acquisition and processing, and data analysis in support of the crustal deformation studies. These activities require the expenditure of $21 to $26M per year from FY 1981 through FY 1985.

The cost of other activities such as the implementation of space systems for global surveys of the earth's potential fields, the development of geodetic application of the Global Positioning System and spaceborne laser ranging, and the development of advanced concepts leading to more efficient, highly-mobile systems have been included. The costs of the space systems are substantial and will need to be justified through the normal budget process.

1.10 INTER-AGENCY AND INTERNATIONAL PARTICIPATION

One of NASA's primary roles in geodynamics is to develop and demonstrate space technology for use by operational agencies. These agencies include the National Geodetic Survey, the US Geological Survey, the National Science Foundation, and the Defense Mapping Agency. These agencies will use data acquired by NASA systems and data from international cooperative programs. The program described in this document has been formulated with the consultation and participation of representatives of these agencies and with leaders of the science community at large. An inter-agency committee has been established to coordinate geodynamics-related activities in these participating agencies. For a description of the coordinated Federal program, see NASA et al. (1979).

Internationally, the European Space Agency and the Interunion Commission on Geodynamics are formulating plans for their geodynamics programs in the decade of the 1980's. NASA and the consortium of US Federal agencies active in geodynamics research will coordinate their programs with those in other countries through ICG, through liaison with ESA, and through other bodies such as the IAG/IUGG Commission on Recent Crustal Movements. This subject is discussed more fully in Section 6.8.

SECTION 2

INTRODUCTION

In this Section we summarize the relevance and importance to modern society of research in global geodynamics and in the cause of earthquakes. We also discuss the evolution of NASA's role in earthquake and crustal dynamic research.

2.1 GEODYNAMICS

In the Overview Section of this document we discussed the importance of continued research into the nature of dynamic processes in the solid earth in terms of observations of regional and global movements and deformations of the earth's crust. Attacks on the very difficult problem of understanding large-scale movements in the earth are being carried out on many fronts using all the techniques of geology, geophysics, and marine science. An international program of coordination of these research programs was started in the 1970's (National Academy of Sciences, 1973) and is being broadened and more sharply focussed in a plan for the 1980's (National Academy of Sciences, 1979). Measurement of how lithospheric plates are moving at the present time and deforming in response to the driving forces is fundamental to achieving the objectives of this research program.

2.2 EARTHQUAKE RESEARCH

Earthquakes and attendant phenomena such as fires and tsunamis are among the most dangerous of natural hazards. Many millions of lives have been lost in historical times as a result of earthquakes, and the potential for loss of life and devastating property damage in the United States is demonstrated by the relatively recent occurrence of disasters not only in California and Alaska, but also in eastern cities such as Boston and Charleston, South Carolina.

The progress of scientific research into earthquake processes made it feasible in 1977 for the Federal Government to initiate a broad program in earthquake hazard reduction. The program is being led by the US Geological Survey and the National Science Foundation. It involves an attack on all aspects - scientific and social - of earthquake risk (Wallace, 1974; National Academy of Sciences, 1976; Office of Science and Technology Policy, 1976; USGS, 1979). The part of this program relevant to the NASA program described here is that aimed at elucidating the basic physical mechanisms of earthquake processes - how and why earthquakes occur. The intention is to lay the foundation for a practical method of earthquake prediction which is well based in scientific understanding. The NASA program of observations of crustal movements over distances beyond the capability of existing classical surveying methods is expected to make important contributions to understanding earthquakes.

2.3 THE ORIGIN OF THE NASA PROGRAM

NASA's program in geodynamics and earthquake research began with the National Geodetic Satellite Program (NGSP) in 1964 (Henriksen and Mueller, 1974; Smith et al., 1976; Henriksen, 1977). The objective of this program was to coordinate the diverse efforts in satellite geodesy, begun with the launch of Explorer 1 in 1958, and to improve the geodetic and geophysical constants used by NASA in its computation of orbits. In addition to NASA, participants in this program included the Department of Defense (Anderle, 1974), the National Geodetic Survey (Schmid, 1974), the Smithsonian Astrophysical Observatory (Gaposhkin, 1974), and the Department of Geodetic Science at the Ohio State University (Mueller, 1974). Satellites launched under this program included GEOS-1, GEOS-2, Pageos, Anna, and Beacon Explorers B and C, the latter two equipped with laser retroreflectors. The NGSP achieved its three-part goal of tying together the world's geodetic networks with 10-meter accuracy in a single center-of-mass system, representing the gravity field to degree and order 15 with an accuracy of 5 parts in 10^8, and intercomparing its major tracking systems at the 10-meter level.

Although the NGSP was begun simply as an effort to improve the geodetic constants, it soon became evident that a sufficient improvement in the accuracies obtainable could lead to the ability to make direct measurements of crustal deformation and plate motion. A conference was held at Williamstown, Massachusetts, in 1969, at which NASA representatives met with leaders of the science community to outline the needs and objectives of a large-scale NASA program in geodesy, geodynamics, and oceanography (NASA, 1969). This led to the development of an Earth and Ocean Physics Applications Program (EOPAP) plan in 1972. This plan called for the development of centimeter-level VLBI and laser ranging systems, as well as a number of flight missions, including Lageos, Seasat 1 and 2, GEOS-3, Magsat, and Geopause-Gravsat.

GEOS-3, with a high accuracy altimeter, and Lageos, a passive satellite with 426 laser retroreflectors, have been successfully flown. The ill-fated Seasat was launched in June 1978 and operated for 99 days; Magsat will be launched in 1979. GEOS-3 altimeter measurements have led to great improvements in our knowledge of the gravity field over ocean areas. The geoid has been determined to the one-meter level over most of the ocean surface. Laser ranging measurements to GEOS-3 and Lageos have resulted in two greatly improved models of the earth's gravity field, GEM 9

and 10 (Lerch et al., 1977). Use of these gravity models has reduced the radial uncertainty in GEOS-3 (long-arc three-to-five day) orbits from 5 meters to about 1 meter. Recent results of the GEOS-3 mission are reported in a special issue of the Journal of Geophysical Research (1979).

Development of laser ranging and VLBI systems has led to substantial improvements in the accuracy of baseline measurements. A series of satellite laser ranging measurements beginning in 1972 under the San Andreas Fault Experiment (SAFE) has resulted in the finding that the 900 km baseline between San Diego and Quincy, California, on opposite sides of the San Andreas fault, appears to be shortening at the rate of about 9 cm/year (Smith et al., 1979). Transcontinental measurements of the 4,000 km baseline between Haystack Observatory, Westford, Massachusetts, and the Owens Valley Radio Observatory near Big Pine, California, over a 2-1/2 year period show a root-mean-square scatter of 7 cm about the mean value (Robertson et al., 1979), and more recent results indicate that this uncertainty has been reduced to about 4 cm. Lunar laser ranging measurements from telescopes at Ft. Davis, Texas, and the LURE Observatory at Haleakala, Hawaii, are expected to achieve better than 10 cm baseline accuracies between these two stations.

Lunar laser ranging was developed in the late 1960's as part of the Apollo program. The objectives of the lunar laser ranging experiment, which placed retroreflectors on the Moon, included the precise determination of positions on the earth's surface, in addition to contributions to relativity, lunar science, lunar geodesy, and celestial mechanics. A detailed discussion of the history, development, and present activities in this program is given in Appendix A.

SECTION 3

SCIENTIFIC BACKGROUND

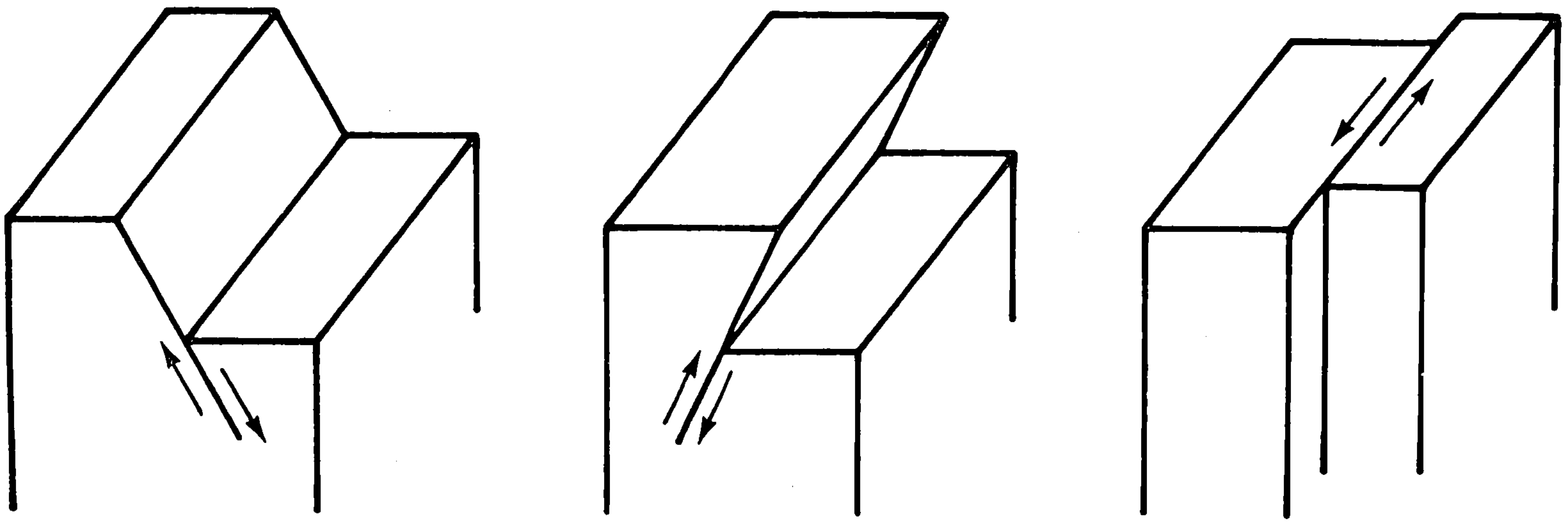
In this section we discuss the scientific principles associated with earthquakes and global geodynamics. The emphasis is on basic concepts and on those phenomena which are amenable to study by space techniques.

3.1 BASIC PRINCIPLES

A fundamental characteristic of an earthquake is the rapid, concentrated release of energy stored in the strain field within the earth. In order to understand how the energy becomes stored and concentrated prior to an earthquake and to understand why, when, and where earthquakes occur, it is necessary to consider some of the physical processes occurring in the earth.

The earth's interior is divided radially into distinct regions: the inner and outer cores, the lower mantle, the asthenosphere, and the lithosphere. The solid inner core extends from the center of the earth to a radius of about 1200 kilometers. The outer core extends out to a distance of about 3500 kilometers. This part of the core is liquid, and is probably composed primarily of iron (the main geomagnetic field is thought to originate by action of a heat-driven dynamo in the outer core). Above the core lies the mantle which extends to within a few hundred kilometers of the earth's surface at 6375 kilometers from the center. The mantle is composed primarily of iron-magnesium silicates.

The top of the upper mantle is a region of lower viscosity and higher seismic absorption called the asthenosphere, and above this is the lithosphere, colder and stiffer than the underlying material. The outer part of the lithosphere is usually referred to as the crust. The lithosphere is now known to be broken up into several large and many smaller plate-like blocks which are in continual motion on a geologic time scale, moving at rates of a few centimeters per year. The continents are carried along on the lithospheric plates like children on rafts. The crust varies in thickness from less than 10 kilometers in oceanic regions to 30 or more kilometers in continental regions.



a. NORMAL FAULTING

b. REVERSE FAULTING
(THRUST FAULTING)

c. STRIKE-SLIP FAULTING

Figure 3.1-1. Relative motion for normal, reverse, and strike-slip faulting.

The nature of the boundaries between these major radial divisions of the earth is not clearly understood at present. Solid-solid phase changes in the constituent minerals, chemical changes, and a solid-liquid phase change at the inner core boundary are involved.

A major difference between the lithosphere and the underlying asthenosphere is in their rheological properties. The lithosphere is more rigid and responds to stress by elastic deformation and rupturing by brittle fracture under sufficiently high stress. In contrast, the underlying asthenosphere deforms by plastic flow in response to loading. The difference in rheology is a consequence of the higher temperatures in the asthenosphere, which alter the mechanical properties of the rock. Study of these rheologies is a major effort in the earthquake research program today (Melosh and Raefsky, 1979; Savage and Prescott, 1978).

The unifying theory of plate tectonics, developed in the early 1960's, explains the relative motion between different portions of the lithosphere and the interaction of the lithosphere with the asthenosphere. Current knowledge of the nature of the forces that drive the plates and the way the plates respond to these forces is very limited. The leading candidates for mechanisms that contribute to plate motion are thermal convection in the mantle, negative buoyancy of the subducted parts of the plates, and gravitational sliding down from topographic highs maintained by thermal expansion at ocean ridges. Whether or not mantle convection is the dominant driving force, there is certainly a return flow through the asthenosphere of the material consumed as subduction occurs and there must be shear stress at the base of the lithosphere. Whether it is retarding or helping the plate motion, the resulting viscous drag on the underside of the lithospheric plates influences plate motion and deformation. For example, Harper (1975) has discussed the effect on plates of vortices that may exist around the ends of subducted slabs. Many geophysical phenomena, including earthquakes, are the result of activity along or near plate boundaries.

There are three main types of boundaries. At the ocean ridge system of plate boundaries, upwelling mantle material cools and solidifies to form new lithosphere. The ridges are marked by extensional movement, spreading, and normal or extensional faulting (fault nomenclature is explained in Figure 3.1-1). At convergent plate boundaries, lithospheric material is consumed by subduction into the underlying mantle. These boundaries are areas of compressional movement and are frequently marked by trenches and reverse or thrust

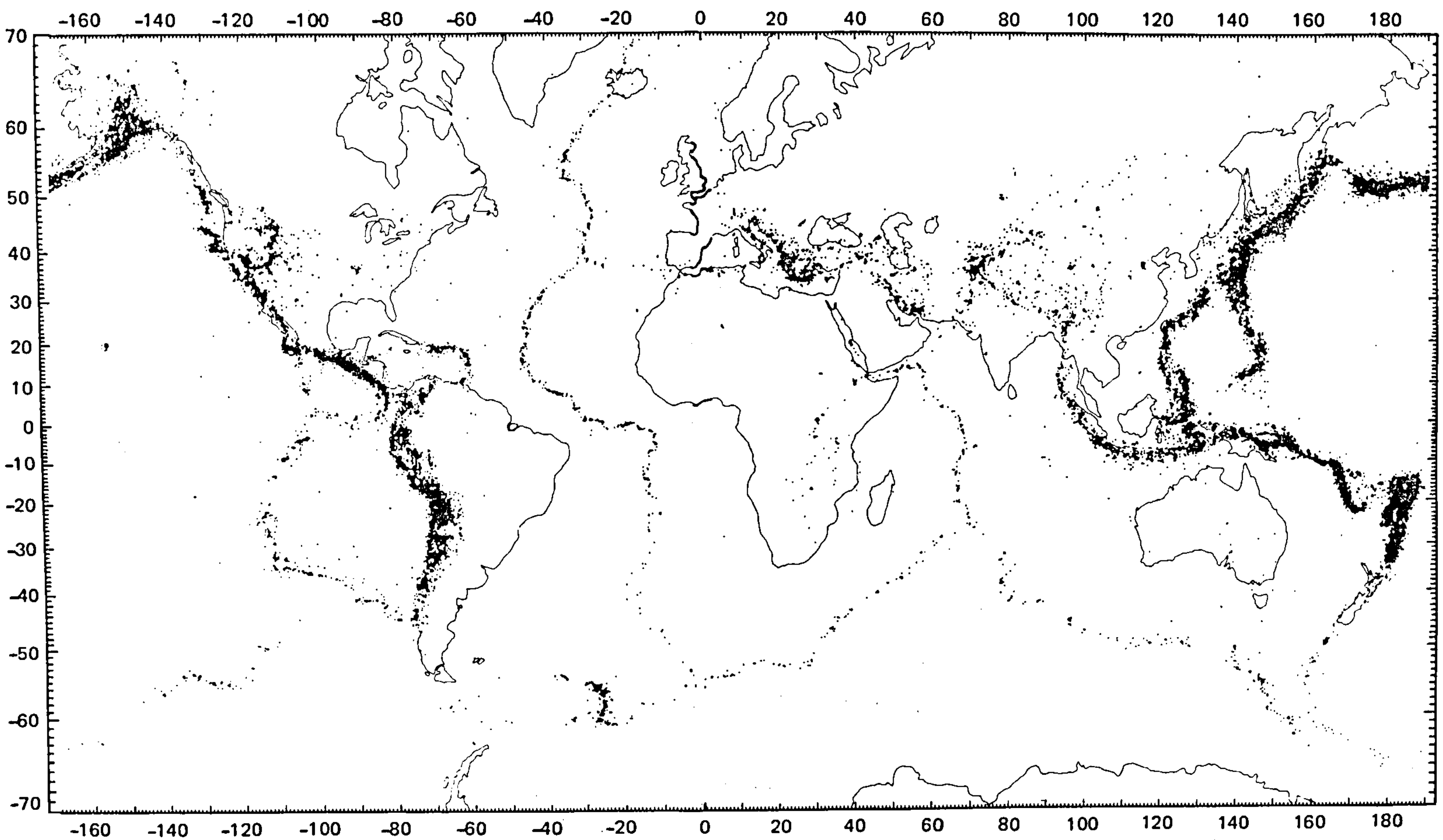


Figure 3.1-2a. Epicenters of 29,000 earthquakes, 1961-1967, depth 0-700 km (from Barazangi and Dorman, 1969).

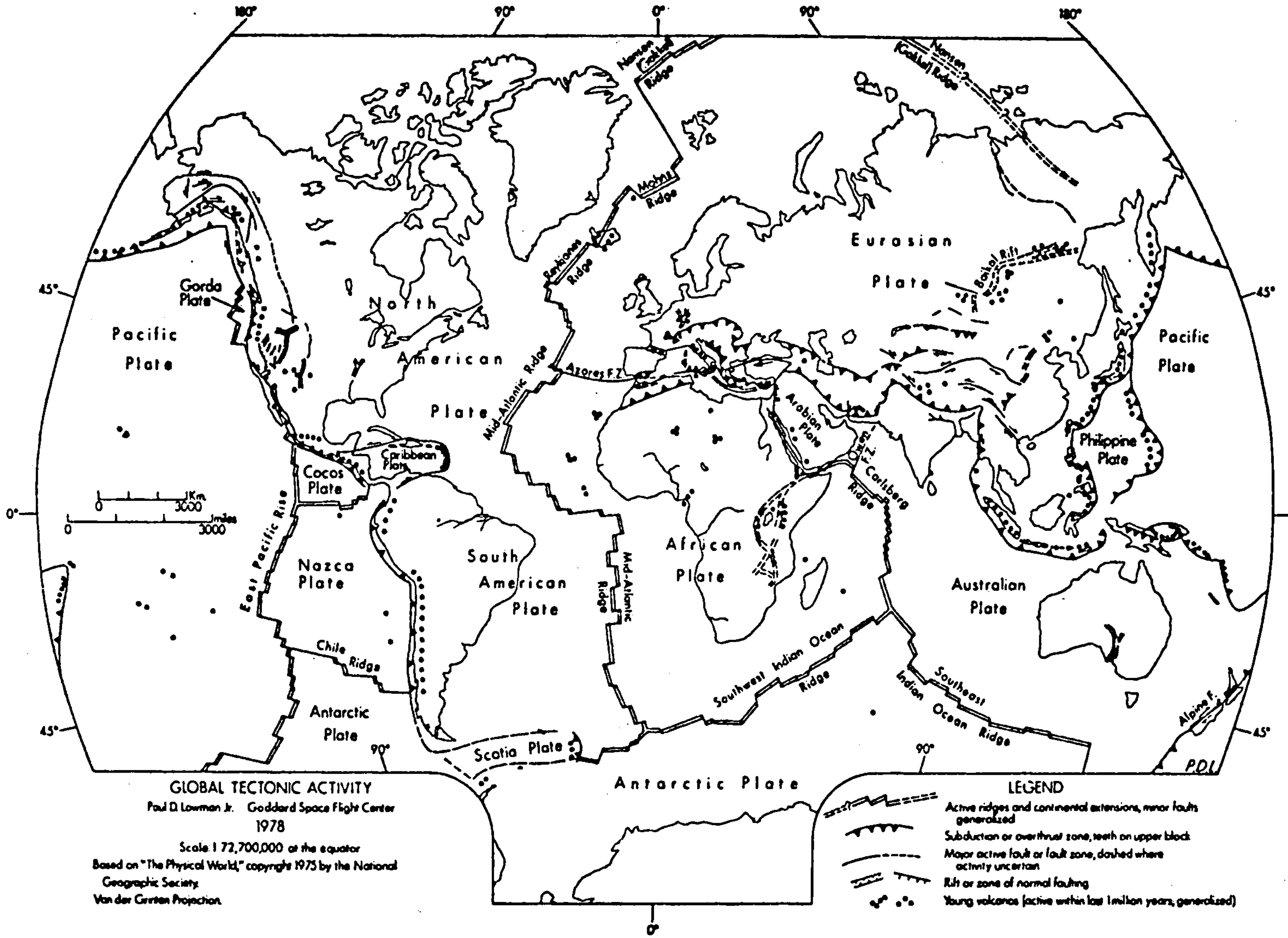


Figure 3.1-2b. Global tectonic features (from Lowman and Frey, 1979).

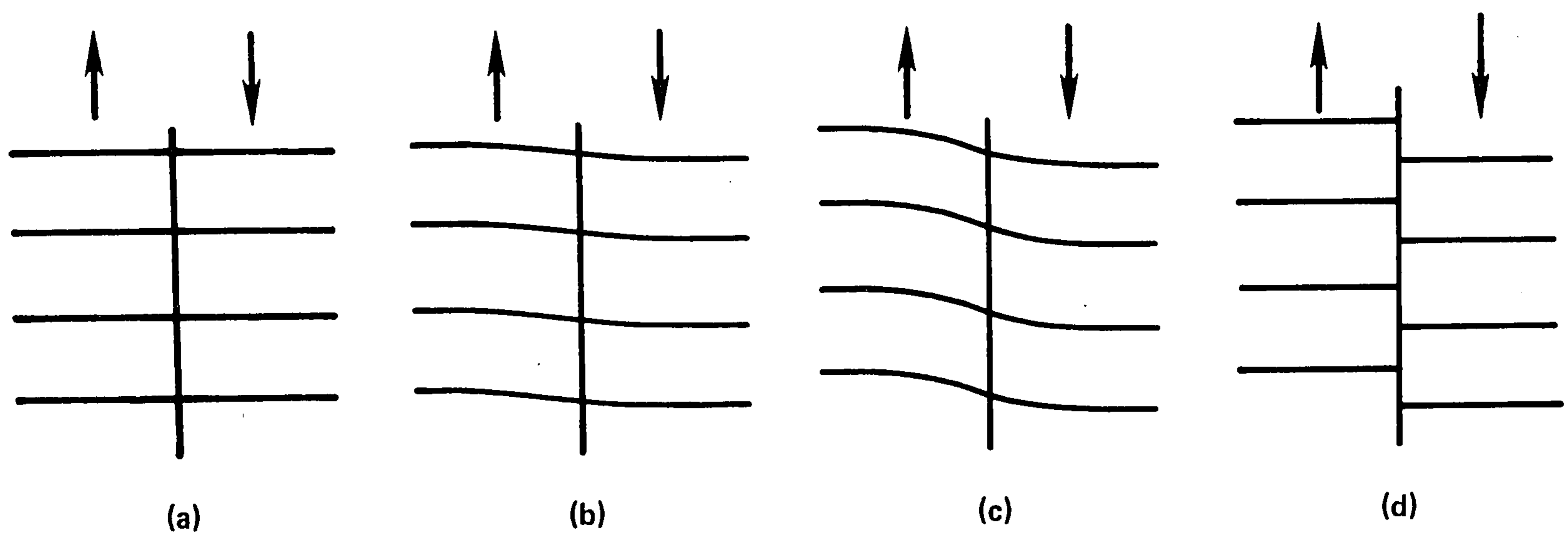


Figure 3.1-3. Sequence of events in elastic rebound theory of earthquake occurrence. Regional shearing movement causes elastic strain to build up from the unstrained state (a) to state (c), when strain is released by fault rupture, producing displacements shown in (d) (from Stacey, 1977).

faulting. At some boundaries the plates slide horizontally past one another with neither creation nor destruction of the lithosphere. Faults along these boundaries are strike-slip faults such as the San Andreas Fault in Western North America or the Alpine Fault in New Zealand. These boundaries do not consist of single faults as in Figure 3.1-1c: the plates are usually broken up by auxiliary faults for a considerable distance on either side of the boundary.

The interaction of plates at their boundaries results in earthquakes. The locations of worldwide earthquakes, shown in Figure 3.1-2a, to a large extent delineate the boundaries between the plates (Figure 3.1-2b). Most earthquakes occur within the lithosphere, but many also occur in the upper mantle where slabs or broken-off pieces of subducted lithosphere are sinking into the asthenosphere. About 75 percent of the energy released in shallow earthquakes occurs in the belt circumscribing the Pacific Plate and adjacent smaller ocean plates; another 23 percent is released in the belt crossing Asia and the Alps, and only about 2 percent of the energy is released in other locations (Stacey, 1977).

The mechanism for shallow earthquakes is simple in principle but very complicated in detail and is not fully understood at present. Elucidation of the exact process by which rupture occurs is a basic objective of the Earthquake Hazard Reduction Program. In simplest form, the present model can be described as follows: Consider a fault separating two plates in relative motion and draw imaginary lines across the fault as shown in Figure 3.1-3. As time progresses the plates on opposite sides of the fault undergo relative displacement except in the vicinity of the fault, where friction and the presence of irregularities or asperities along the interacting boundaries impedes motion. Because of the imposed shearing motion, shear strain accumulates near the fault and the initially straight lines are deformed. Eventually the accumulated stress along the fault becomes so great that the shear stress exceeds the shear strength of the rock, resulting in rupture. The stress and the strain are relieved, at least partially, by the subsequent rapid displacement. The orientation of the fault plane and the direction of slip in the fault plane can be determined from seismic observations. Such focal mechanism studies have been very important in determining the state of stress and relative motion in active seismic regions. To many seismologists, the first really conclusive evidence for the plate tectonics model came from focal mechanism studies of earthquakes along the transform faults that offset ocean ridges (Sykes, 1967).

Present models for earthquake mechanism and post-seismic movement have reached a fairly sophisticated level (see, for example, the special issue of the Journal of Geophysical Research devoted to faulting mechanisms (1979); Thatcher and Rundle, 1979; or Melosh and Raefsky, 1979).

Recent studies of long-period seismic waves have shown that large earthquakes are also accompanied by creep or non-rupture phenomena whose nature is not well understood at present (Kanamori and Cipar, 1974).

Although most earthquakes take place at plate boundaries, some events, even major ones, occur well within recognized plates. Examples within the United States include the New Madrid earthquake of 1812 and the Charleston earthquake of 1886. This implies that residual regional and local stresses exist in the interior of plates and that seismic hazards cannot be understood exclusively by reference to a small number of rigid plates. The present plate tectonics model does not account for these intraplate stresses, nor for the large-scale vertical movements known to have taken place on the basis of geologic studies.

Intermediate and deep-focus earthquakes are usually associated with the subduction process. The source mechanism is consistent with extensional failure of the subducted slab at intermediate depths, and compressive failure at greater depths where the slab runs into more resistive material in the mantle below 650 km.

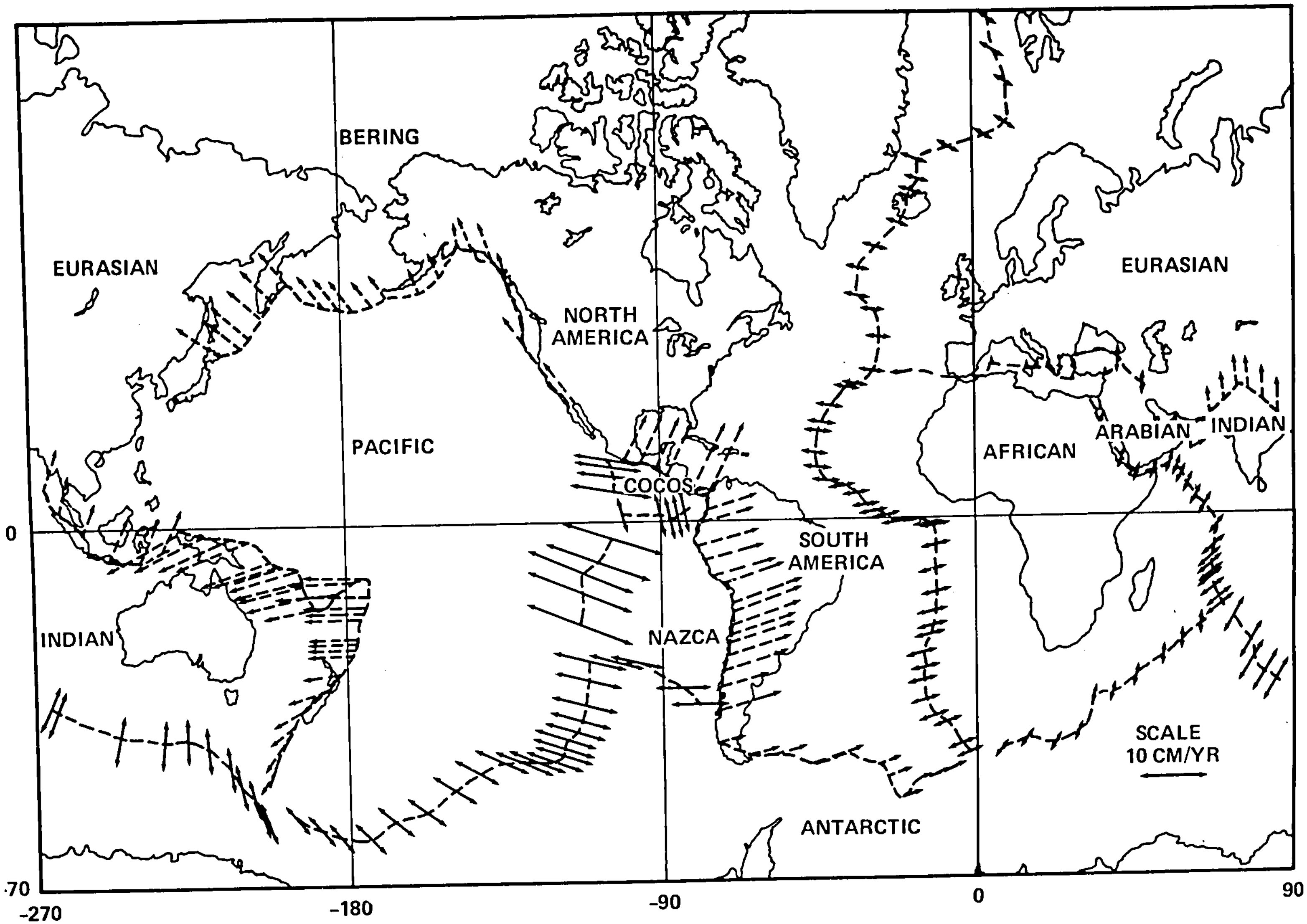


Figure 3.2-1 Motion at tectonic plate boundaries (from Minster et al., 1974).

3.2 GLOBAL, REGIONAL, AND LOCAL-SCALE PHENOMENA

The phenomena associated with earthquakes range from the radiation of elastic waves affecting the whole earth to cracking in rocks on a microscopic scale. In this subsection we describe some of these phenomena, emphasizing observable physical processes, particularly those antecedent to an earthquake. For this purpose it is convenient to divide the phenomena into global, regional, and local scales. On each of these scales, motions in the earth or changes in its physical state provide information which contributes to the understanding of where and how earthquakes occur.

3.2.1 Global-Scale Phenomena

Global-scale phenomena are those which involve the earth as a whole or segments of it comparable to size to the larger tectonic plates. In this section we discuss these alone, reserving discussion of smaller-scale phenomena to later sections.

3.2.1.1 Interplate Motions

From the standpoint of earthquake risk assessment, the most fundamental global-scale phenomenon is the relative motion of the tectonic plates. An elementary theorem in kinematics is that the most general instantaneous motion of two rigid bodies on the surface of a sphere is a relative rotation of the two bodies about an axis passing through the center of the sphere. Neglecting the ellipticity of the earth, this implies that every lithospheric plate is rotating with respect to every other plate. When the pole of relative rotation is far away from the two plates, they move rapidly; when the pole is located on one of the plates or near the boundary, the relative movement is slow (see, for example, Figure 4.4-2). Plates can be converging along a boundary, diverging (as at the ocean ridge system), or sliding past one another. The relative plate movement measured in linear units (centimeters per year, for example) thus varies along the plate boundaries. Figure 3.2-1 shows an estimate of relative plate velocities from geological, seismic, and geophysical evidence (Minster et al., 1974). The length of the vectors on the figure indicates velocity, which is greatest (about 18 cm/yr.) along the Nazca-Pacific boundary. An indication of the rate of strain accumulation along the fault can be deduced by comparing the relative velocities of adjacent plates with their apparent local velocity. For example, the Pacific and North American Plates should have a relative speed of 5-6 cm/yr along the San Andreas Fault. Measurements across some portions of that fault show little

or no movement at present; in these areas, strain is accumulating at a rate corresponding to a plate motion of a few centimeters per year (for a review, see Savage, 1978). One of the justifications of the Earthquake Hazard Reduction Program is that this strain energy may be released at any time in the form of one or more large earthquakes, potentially catastrophic to sizeable areas.

Major earthquakes may cause a redistribution of the stress field in the lithosphere and a change in the moment of inertia tensor of the earth, because of the redistribution of mass. The earth's polar motion may be affected at observable levels by such changes. This is discussed further in the next section.

One manifestation of a propagating stress field following a major shock is the migration of earthquake epicenters. If a region is pre-stressed to near the critical value for earthquake occurrence, then a passing additive stress field may trigger the event; over global distances a succession of events may be triggered. In this case a pattern of earthquake occurrence will develop with the locations of some earthquake epicenters propagating with characteristic velocities. There is some evidence suggesting that just such a pattern of earthquake migration exists in worldwide seismicity (Kagan and Knopoff, 1976; Minster, personal communication, 1978).

Another manifestation of stress redistribution is the propagation of "strain waves" of displacement across a plate, eventually representing a shift in the position of the plate relative to its neighbors (Anderson, 1975). How such shifts take place is completely unknown at present. This question is one that should be answered with the help of the precise position data that will be gathered in the NASA crustal dynamics program.

3.2.1.2 Polar Motion and Earth Rotation

The instantaneous axis of rotation of the earth moves in a roughly circular path with respect to its figure axis. The motion is slow and has several frequency components, including an annual term and a comparable movement with a period of about 428 days (the Chandler wobble). The amplitude of the movement is several meters. The mechanism of excitation of this "wobble" is poorly understood (for a review, see Lambeck, 1978). The major contributors to the annual term are seasonal movements of the atmosphere and

seasonal changes in ground water level (Munk and MacDonald, 1960, p. 130). It is surprising that the effects even include the rising of sap and falling of leaves from trees in alternate hemispheres (Jeffreys, 1916). The seasonal effects on the Chandler wobble are discussed by Wilson and Haubrich (1977) and Stolz (1976). The 428-day period of the Chandler wobble has been explained by Smith (1977). It has been suggested that there is some correlation between the occurrence of large earthquakes and changes in the path of the instantaneous pole of rotation, that is, in the excitation of the Chandler wobble (Mansinha and Smylie, 1967; Smylie and Mansinha, 1968). Theoretical calculations of the expected changes for large earthquakes fail to explain the observed changes, although Kanamori (1977b) showed that taking into account the non-radiative precursory creep of the 1960 Chilean earthquake brings the predicted shift to within a factor of two of that suggested as having been observed near the time of the earthquake. The present operational method of measuring polar motion (using astronomical latitude observations) has an accuracy of between 40 cm and one meter, with five-day averaging times, which is inadequate to determine the irregularities in polar motion to the accuracy required to answer the question of a relationship between earthquake occurrence or plate motion. The NASA and NGS geodynamics programs will use space techniques to determine polar position to a few centimeters and, it is hoped, provide valuable insight into the excitation of this motion.

In addition to polar motion, irregular fluctuations in the length of the day (the rotation rate) exist, amounting to a few milliseconds. These fluctuations are distinguishable from the steady slowing of the rotation due to gravitational gravity interaction of the Moon and Sun with the earth, and from seasonal variations due to movements of large atmospheric masses. Some evidence exists of a correlation (on a time scale of decades) between fluctuations in rotation rate, excitation of polar motion, and other geophysical phenomena such as earthquakes, the drift of the dipole geomagnetic field of the earth, zonal wind changes, and volcanism (e.g., Anderson, 1974, 1975; Press and Briggs, 1975).

3.2.1.3 Gravity and Convection Dynamics

The gravity field of the earth reflects the distribution of mass within the earth, and gravity anomalies are features in the earth's gravity field that indicate inhomogeneities in this distribution. As such, the gravity anomalies contain information that is important in constructing models for dynamics processes taking place in the

interior of the earth (National Academy of Sciences, 1978). For example, gravity anomalies and geoid undulations have been associated with major topographic features such as the Mid-Atlantic Ridge, the continental margin of the Eastern United States, and the Bermuda Swell. Near most ridges, the subsidence of the sea floor away from the ridge can be predicted from a model based on thermal cooling. A geoid profile derived from this model closely resembles the measured profile obtained from GEOS-3 altimetry (Haxby and Turcotte, 1978). The geoid over the Eastern continental margin has been explained by isostatic compensation and that over the Bermuda Swell by Pratt compensation with a 100 km depth of compensation (Haxby and Turcotte, 1978). Thus, gravity anomalies contain information on mass distributions within the earth and deformations of the lithospheric plates that may provide insight into basic tectonic mechanisms (Kaula, 1969).

3.2.2 Regional-Scale Phenomena

Regional-scale phenomena occur over distances less than the dimensions of typical tectonic plates, a few thousand kilometers, but larger than a few hundred kilometers.

3.2.2.1 Regional Deformation and Motion Along Faults

The areas around seismically active faults are regions of strain accumulation, or deformation. The strain rate is a key factor in determining the frequency of earthquake occurrence, and the accumulated strain at the time of the rupture is a principal element in determining the magnitude of expected earthquakes. The spatial extent of the faulting is also correlated with the regional strain accumulated prior to rupture. If the interior of a plate is moving with respect to a regionally locked portion of its boundary, then the strain accumulation is related to the size of the region undergoing deformation. For examole, if the relative velocity is 5 cm/yr and all the strain is accommodated within 50 km of the fault, the average strain rate is about 10^{-6}/yr. Details of how the strain is distributed spatially depend on geological factors, but in general higher strain rates are experienced near the fault and lower rates in areas more distant. While a strain rate of 10^{-7}/yr is typical along the San Andreas Fault, it is not known how far back into the plate interior a significant strain extends.

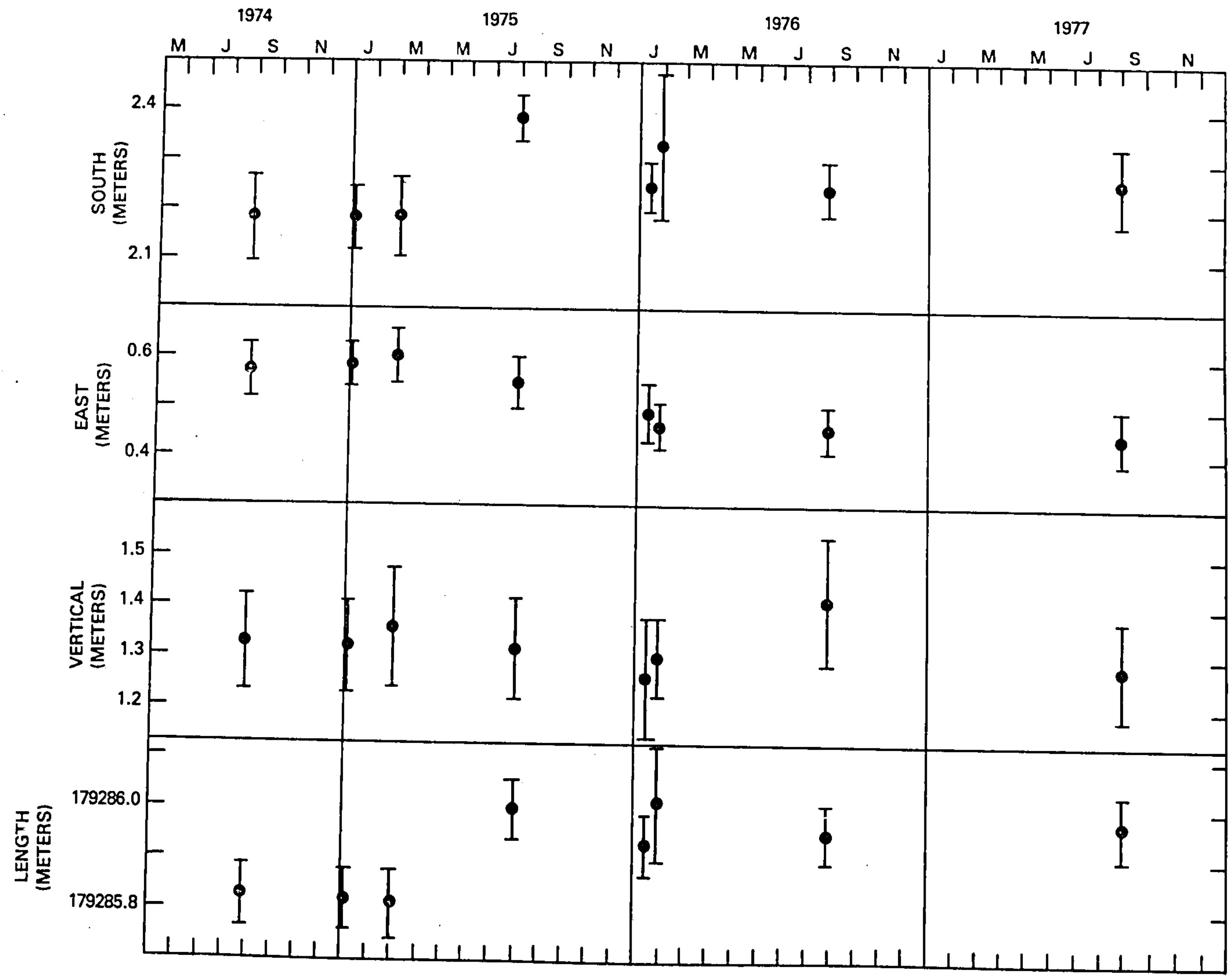


Figure 3.2-2. VLBI measurements, Pasadena to Goldstone (from Ong et al., 1977).

Not all regions along a fault respond in the same manner to the driving forces creating the interplate motions. For example, the regions around Los Angeles and San Francisco seem to remain locked between major earthquakes which occur about once in about 150 years (Sieh, 1978), while in Central California stress is relieved through creep, a slow continuous or episodic motion resembling viscous flow, which is unaccompanied by seismic waves and which may prevent or reduce strain accumulation along the fault (Nason, 1971a, 1971b; Burford and Harsh, 1979; Savage and Burford, 1973). Recent measurements of crustal movement in California suggest that deformations may extend over distances of hundreds of kilometers. The SAFE results from 1972 to 1976 have been interpreted as implying a shortening of the baseline between Quincy in the southern Sierra Nevada and Otay Mountain, near San Diego, of about 9 cm/yr (Smith et al., 1979). The error of measurement is in doubt, but is probably between 3 and 6 cm. Observations in 1974-77 are consistent with a westward movement of Pasadena relative to Goldstone of about 5.6 ± 1.9 cm/yr (Figure 3.2-2). No significant vertical displacements exceeding 5 cm occurred during the period 1974-1977 (Ong et al., 1977). Re-evaluation of ground surveys near the Mexican border suggests right lateral offset along the southward continuation of the San Andreas Fault of about 11 cm/yr (Gergen, 1978; Snay and Gergen, 1978). All these measurements are only roughly consistent with the expected right lateral movement of the plate boundary of about 5 cm/yr. Moreover, taken together with geodimeter surveys at the San Andreas Fault which indicate little or no motion in many areas, the measurements indicate the importance of detailed mapping of the strain field over regional distances.

3.2.2.2 Regional Geology

It is obvious that there is a correlation between the locations of areas of seismic activity and of mountain belts that lie at compressional plate boundaries overlying present or former subduction zones.

Some fold belts, including the Alpine, Appalachian, and Circum-Pacific chains, are characterized by abundant faulting. Strain accumulates along such faults and its release is responsible for much of the seismic activity occurring in continental areas; for example, along the thrust faults marking the southern edge of the Himalayas in India and Burma.

Presumably, all folded mountain belts are seismically active in their youth but may become relatively inactive later. For example, the Urals (an ancient plate boundary) are not marked by any concentration of earthquakes. However, there is considerable evidence that some degree of seismic reactivation can occur in old mountain belts such as the Appalachians in the United States. It was shown by Sbar and Sykes (1973) that the Northeastern United States is under crustal compression which is probably responsible for seismicity along faults in these mountains. However, the main release of stress in the eastern part of North America has occurred in areas such as Missouri and South Carolina that are not usually considered to be mountainous.

Major crustal movements, especially those continued over millions of years, have been revealed by studies of regional geology. For example, Hill and Dibblee (1953) have shown that successively older geologic units of the San Andreas Fault are progressively more offset in a right lateral sense. The data suggest continued strike-slip motion along the fault since the Cretaceous (135 million years ago), with a cumulative offset of several hundred kilometers.

3.2.3 Local-Scale Phenomena

Local-scale phenomena occur in the immediate vicinity (say, 100 kilometers) of a fault or the epicenter of an earthquake. Much of the discussion of deformation, fault motion, and geology for regional phenomena is also applicable here. The extent to which local asperities and frictional forces resist motion and cause strain accumulation determines the extent of faulting and energy release in the subsequent earthquake. The local rock composition and mechanical properties presumably determine the location of the initiation of rupturing, how the rupture propagates, the extent of severe ground shaking, and other effects of the event. Several of the precursory phenomena discussed in Section 3.3 occur on a local scale, including land movement, accelerated creep, changes in ground water level, and local geomagnetic and electric field effects. An approximate relationship between the fault surface area (or aftershock area) S and the surface wave magnitude of the associated earthquake M_s is (Kanamori and Anderson, 1975)

$$\log S = M_s - 4$$

Thus, for $M_S = 3$, $S = 0.1$ square km, while for $M_S = 8$, $S = 10^4$ square km. Areas of comparable size might be affected by precursory geophysical changes, particularly in the case of non strike-slip faulting.

The preceding discussions indicate that on all three scales earthquake-related geodynamic processes occur which are amenable to study by geodetic techniques. Plate motions, changes in local strains, seismic slip, and seismic creep are examples of quantities which are suitable for measurement by space techniques.

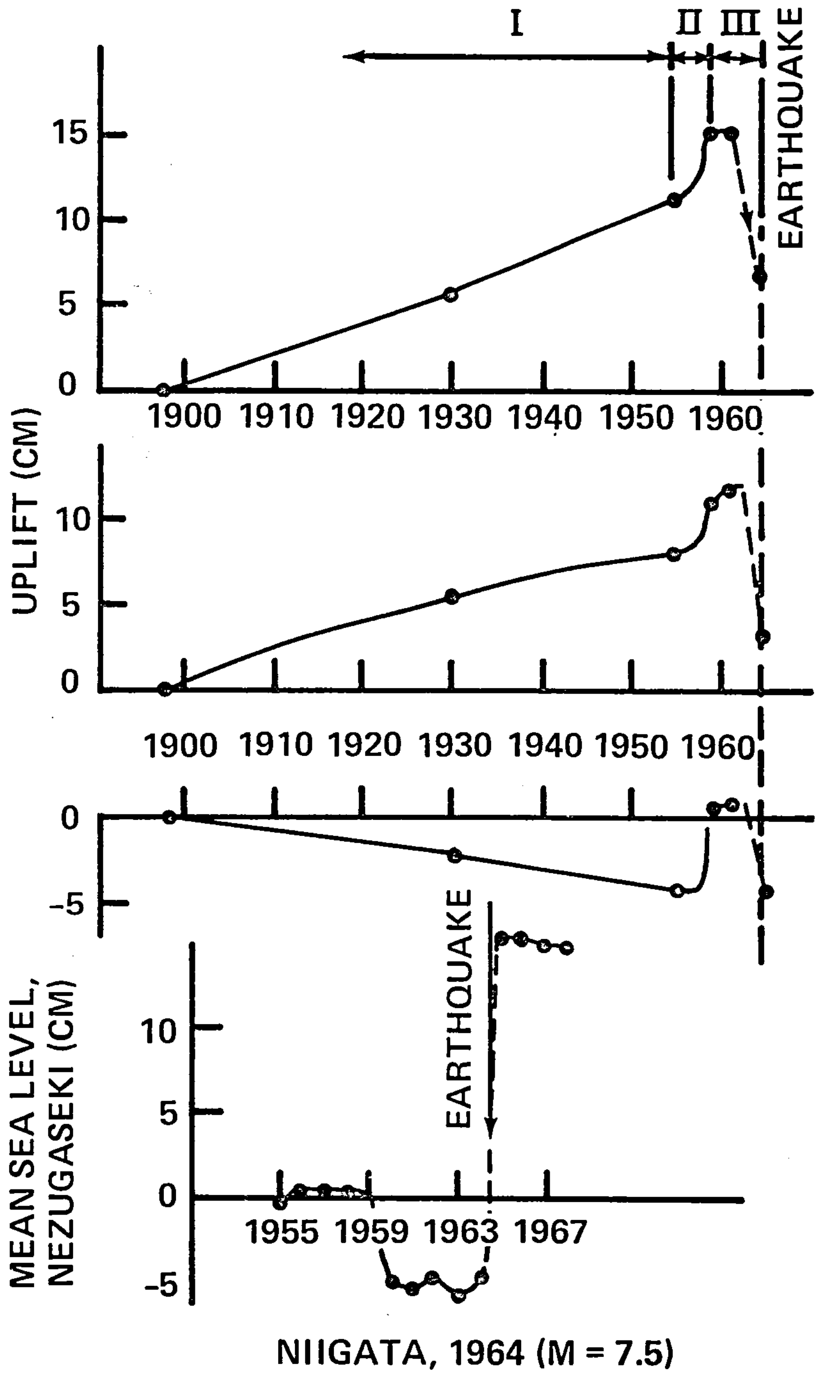


Figure 3.3-1. Anomalous crustal uplift preceding the 1964 Niigata (Japan) earthquake. Top three curves are uplift at selected benchmarks; bottom shows tide gauge data at Nezugaseki (from Scholz et al., 1973).

3.3 EARTHQUAKE PRECURSORS

The ultimate objective of precursor monitoring is to enable the reliable prediction of a forthcoming earthquake. For certain purposes it is convenient to distinguish time scales for prediction. Long-range forecasts, even fairly imprecise in expected location, time, and magnitude, can be used to identify regions that should be intensely monitored. This is the procedure followed in Japan for the designation of "areas of intensified observation" (Rikitake, 1976). Things that can contribute to such a designation include regional and local deformation measurements, the historic seismicity of a region, propagating patterns of seismicity, and the existence of so-called seismic gaps. Short-term predictions (and some longer-range forecasts) are usually made on the basis of such local changes in the physical state of the earth as changes in the propagation velocity of seismic waves, the rate of occurrence of small-magnitude seismic activity, foreshocks, and changes in ground elevation, tilt, or water levels. For the present purpose it is useful to discuss separately precursors based on geophysical measurements and those based on statistical analysis (although actual predictions will probably rely on integrating results from both classes of precursors). This is done in Section 3.3.1 and 3.3.2. In Section 3.4 the current state-of-the-art in earthquake prediction is reviewed.

3.3.1 Geophysical Methods

3.3.1.1 Crustal Deformation

One of the more frequently observed precursors is a deformation of the ground around the epicenter of a forthcoming earthquake (e.g., Wyss, 1977). Some of the deformations that may be related to earthquakes include tilt, changes in elevation, and high rates of strain or creep. One of the best documented cases of anomalous crustal uplift occurred prior to the 1964 earthquake in Niigata, Japan. The measurements, shown in Figure 3.3-1, reveal a smooth vertical movement from 1898 to about 1955-1958. Subsequently, there was a period of rapid uplift terminated by a period of little movement and then a magnitude 7.5 shock.

Along the San Andreas Fault in California a frequently observed precursory phenomenon has been a change in tilt (National Academy of Sciences, 1976). An example of anomalous tilting preceding an earthquake near Hollister, California is shown in Figure 3.3-2.

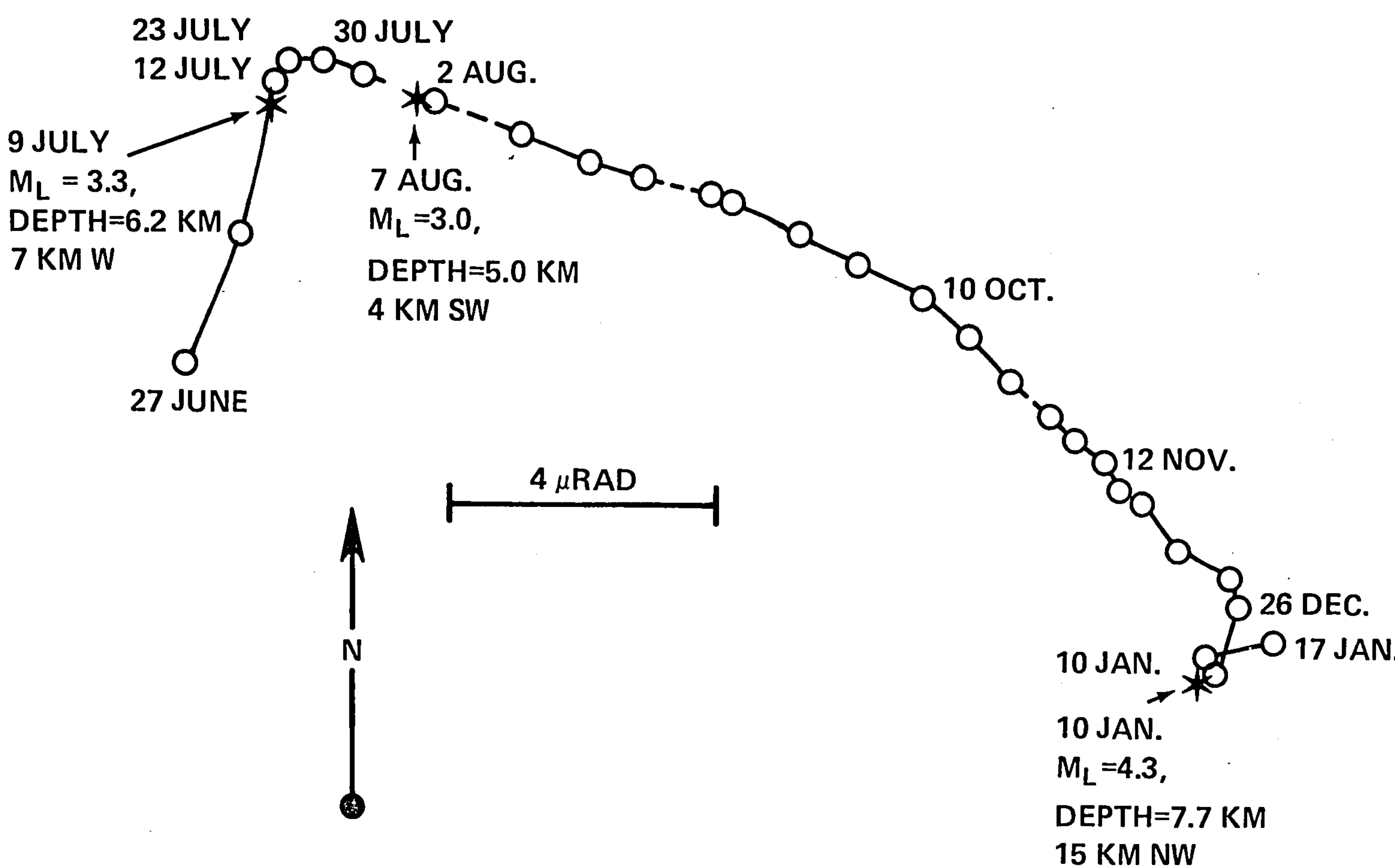


Figure 3.3-2. Cumulative weekly tilt vectors at Nutting, 7 km southwest of Hollister, California, June 1973 to January 1974. Local earthquakes indicated by stars (from Johnston and Mortensen, 1974).

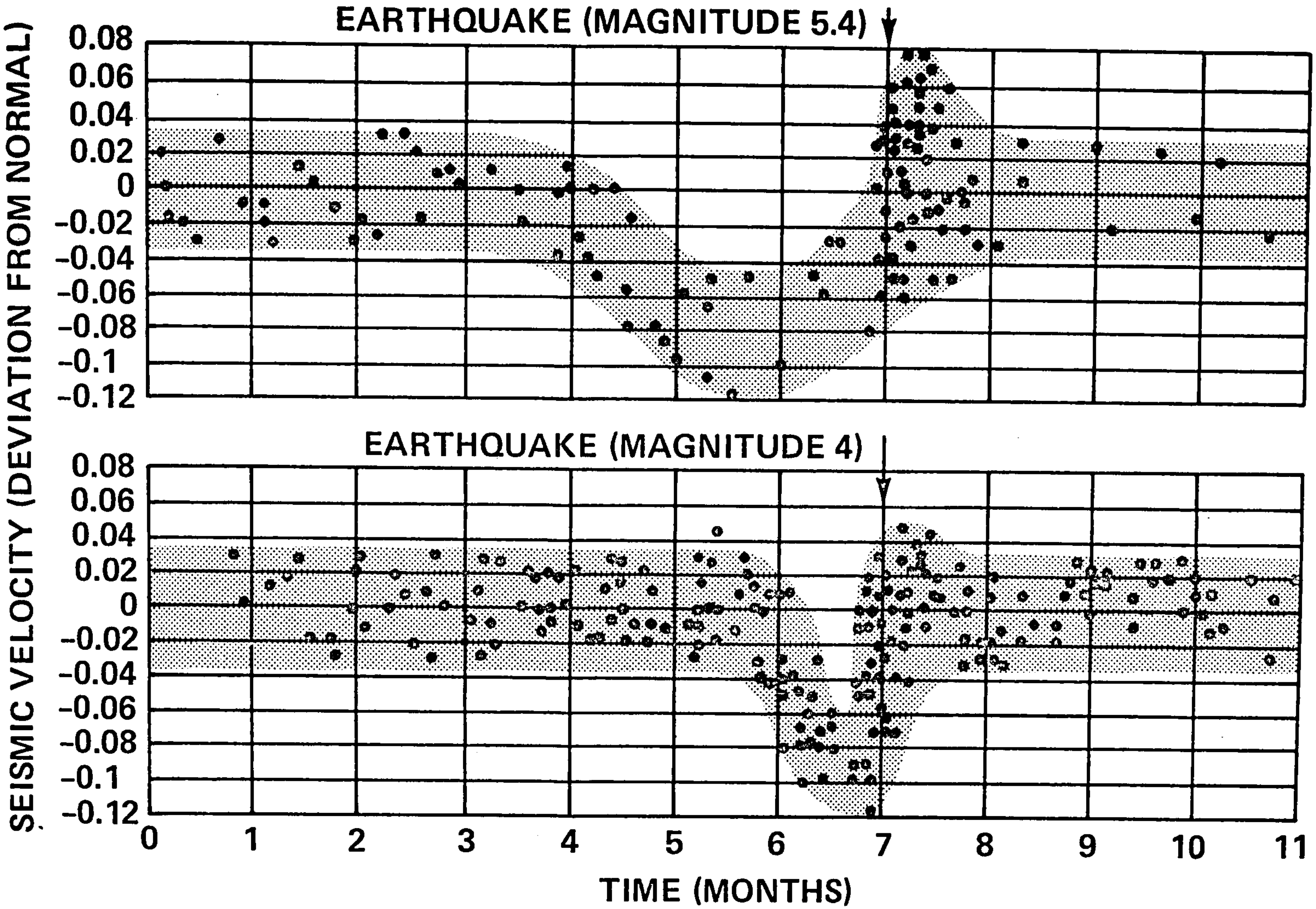


Figure 3.3-3. Premonitory changes in seismic velocity (ratio of compressional wave velocity to shear wave velocity) before two earthquakes in the Garm region of Tadzhikistan, USSR (from Press, 1975).

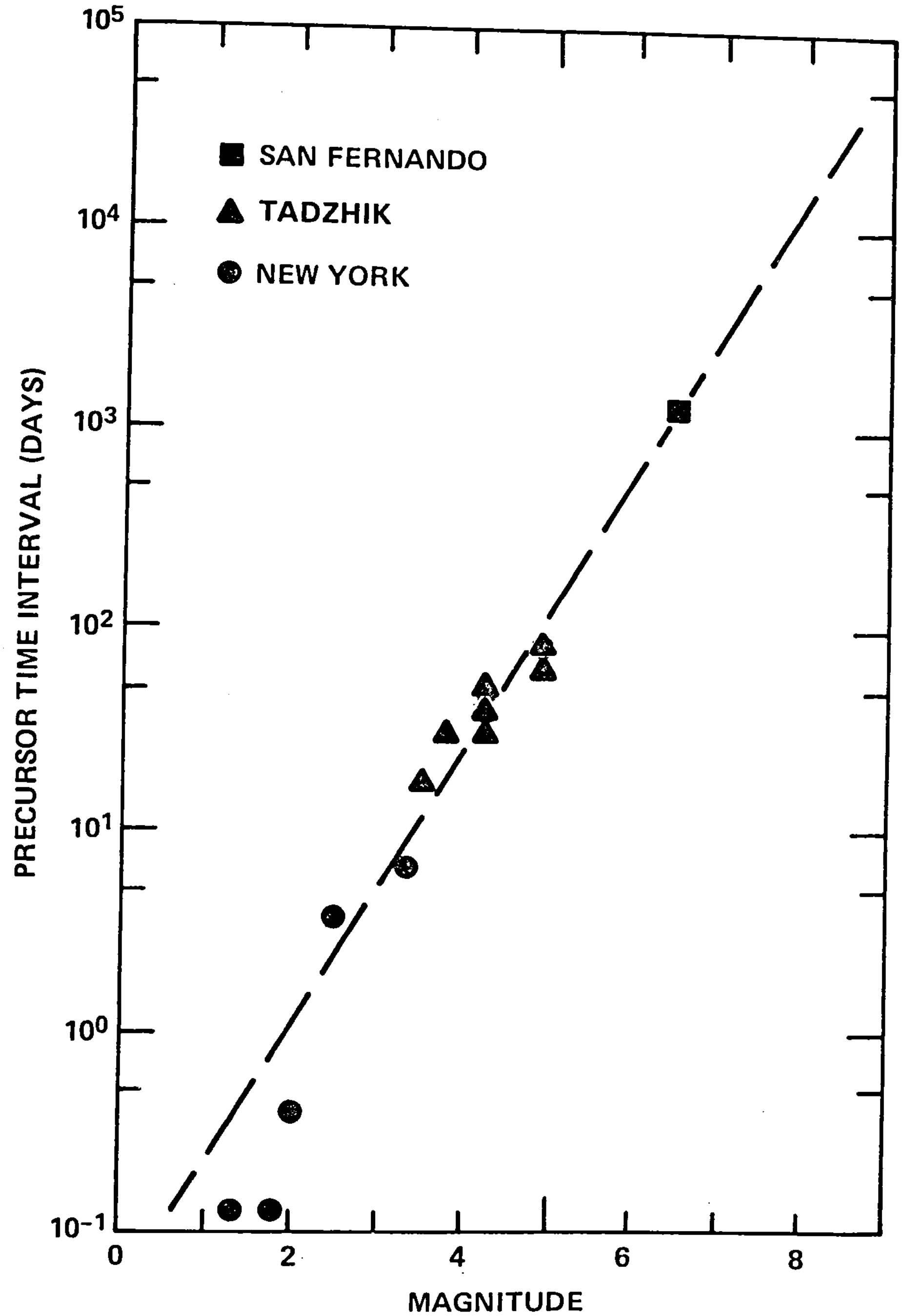


Figure 3.3-4. Time interval for anomalous seismic velocity precursors as a function of earthquake magnitude. Square: 1971 San Fernando earthquake; triangles: data from Semenov (1969); circles: data from Aggarwal et al. (1973). From Whitcomb et al. (1973).

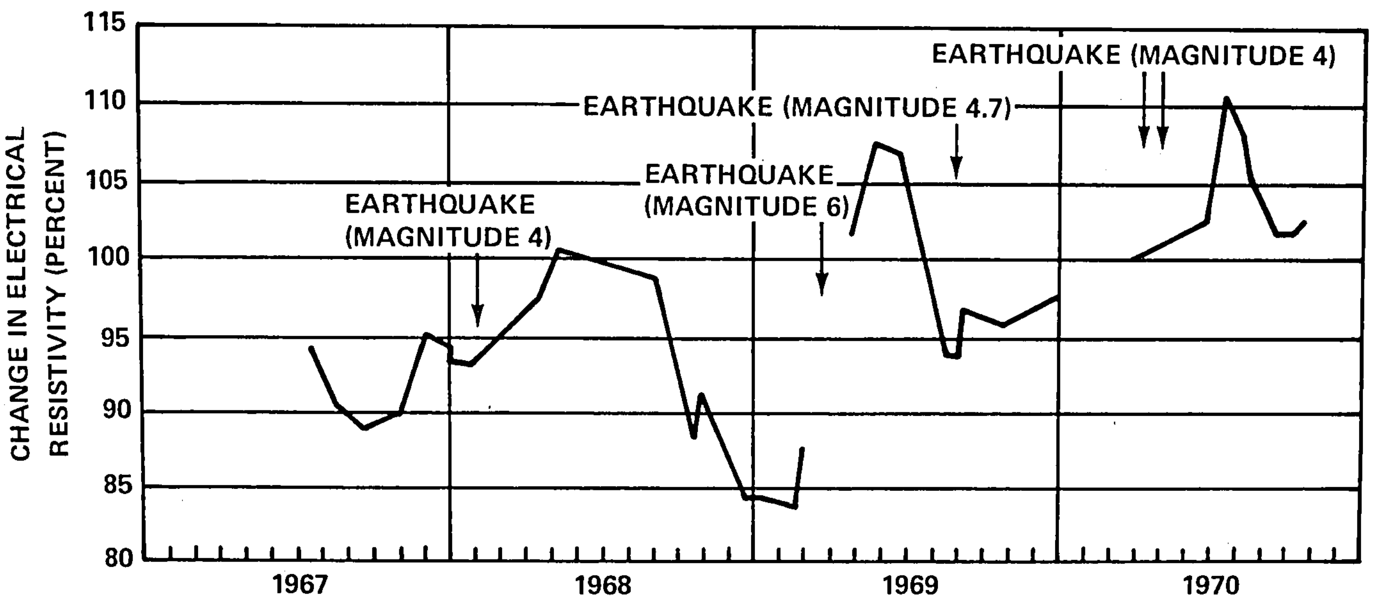


Figure 3.3-5. Changes in electrical resistivity of the crust prior to a series of earthquakes in the USSR between 1967 and 1970 (from Press, 1975).

3.3.1.2 Seismic Velocities

When an earthquake occurs elastic waves are propagated through the earth from the center or focus of the event. The compressional and shear components of the seismic waves travel with different velocities. Several researchers have reported that the ratio of these velocities decreases in a region near the site of a forthcoming earthquake (Figure 3.3-3). Furthermore, as shown in Figure 3.3-4, the longer the duration of the anomalous velocity ratio, the larger the magnitude of the subsequent shock. A magnitude 7 earthquake may be preceded by a 13-year period of anomalous velocity ratios (Whitcomb et al., 1973). Not all earthquakes in regions being studied (e.g., California) show such anomalies, however, and the method may have limited promise for practical earthquake prediction. The physical basis for these anomalies is possibly related to the occurrence of small-scale cracking, and the orientation of these cracks influences the areas over which velocity anomalies can be observed.

3.3.1.3 Gas Concentration in Ground Water; Other Techniques

Radon is a naturally occurring radiogenic gas existing in minute concentrations in ground water because of the decay of uranium in rock. Prior to two intermediate-magnitude earthquakes near Tashkent (USSR), significant increases in the concentration of radon were observed. Radon content has been widely monitored in attempts to determine whether fluctuations might provide precursory signals for earthquakes.

Among other techniques that have been considered for earthquake prediction are measuring variations in electrical currents and magnetic fields. The variation in electrical resistivity between points in the earth's crust separated by a few kilometers shows an apparent correlation between earthquake occurrence and minima in the resistivity (Figure 3.3-5). Other anomalies which appear to be correlated with earthquake occurrence include changes in water level and temperature in wells, accelerating creep, changes in the stress field patterns for nearby seismic events, and unusual animal behavior.

3.3.2 Statistical Methods

Statistical methods for predicting earthquakes begin with the cataloging of the earthquakes occurring in a

particular region. With good historical documentation covering many decades in active seismic regions, fairly reliable long-term interval likelihood estimates can be made. For example, in the Southern California area about five earthquakes of magnitude 6 or greater can be expected during a 20-year interval (National Academy of Sciences, 1976), while the interval for very large earthquakes is about 160 years (Sieh, 1978).

Particularly likely sites for major earthquakes are areas of seismic gaps. These are regions where no earthquakes have occurred in recent time despite relative motion in the adjacent areas, and in some cases these periods of inactivity are terminated by a resumption of seismicity. A recent example of a prediction on the basis of a seismic gap is the Oaxaca area of Southern Mexico (McNally et al., 1979; Singh et al., 1979; Ohtake et al., 1977).

Because the probability for the occurrence of any major earthquake during an interval of a few days is low, *a priori*, statistical techniques are more useful for long-range forecasting than short-range predicting. More important for short-range prediction is the relationship between the frequency of earthquake occurrence and their magnitude. Over a broad magnitude range the frequency decreases as $\log f(m) = a - bm$, where m is the magnitude, which is logarithmically related to the energy content of the seismic waves. Although the value of b may vary from region to region, it remains approximately constant for a given region over long periods of time. However, prior to many earthquakes an increase in the number of small events causes significant departures of b from its normal value. Frequently there is a period of relative quiescence during which b is depressed for some time prior to the major earthquakes, and then a rise in b occurs immediately preceding the main event. The interpretation of foreshocks requires both statistical and geophysical considerations; however, the occurrence of foreshocks has permitted very short-range warnings (hours) of an impending earthquake (Adams, 1977).

3.4 STATE-OF-THE-ART AND POTENTIAL FOR PREDICTION

Major programs aimed at earthquake prediction have been initiated in Japan, the People's Republic of China, the USSR, and the United States. The potential for the United States effort has been summarized by the National Research Council's Panel on Earthquake Prediction, which concluded that "with appropriate committment, the routine announcement of reliable predictions may be possible within 10 years in well instrumented areas, although large earthquakes may present a particularly difficult problem" (National Academy of Sciences, 1976). However, the present state of understanding of earthquake precursors, and the relatively sparse field instruments now operating, do not permit routine prediction at this time.

The evaluation of prediction capability focuses on two elements: (1) the success-failure ratio for prediction of actual events; (2) the false-alarm frequency.

For a group of magnitude three earthquakes in California, Johnston has reported, "In 25 cases our instruments had earlier seen anomalies...but ten similar observations were not followed by quakes; before every quake we detected a precursor" (Canby, 1976). Based on these results and others obtained in areas of dense instrumentation, it appears that failures to predict may be more likely the result of sparse or inappropriate instrumentation than the absence of precursory phenomena. However, no one precursor has been shown to be a reliable indicator for all earthquakes; rather, predictions of different earthquakes have been made on the basis of different observations.

Particularly important but difficult to predict are large earthquakes. The duration of an anomaly is likely to be monotonically related to the magnitude of the subsequent earthquake, and a similar period of time must elapse before it can be determined that anomaly recovery has occurred. Since the time span for a precursory anomaly for a large event may be many years, it is difficult to recognize the anomaly and to determine with any useful resolution the expected time for the earthquake. Thus, the successful prediction of the magnitude 7.3 earthquake in Haicheng, China, in 1975 is especially noteworthy (Raleigh et al. 1977). After some initial false alarms the successful

prediction preceded the actual event by 5-1/2 hours. Although the magnitude 8.2 Tangshan, China, earthquake in 1976 was not predicted, there have been reports of gravimetric anomalies associated with this event (Adams, 1977; Wang, 1978). Thus, while initial routine predictions will probably be made only for small magnitude events, the NRC panel notes that "most researchers are optimistic that we will eventually be successful in predicting large earthquakes as well" (National Academy of Sciences, 1976).

3.5 CONVENTIONAL SEISMOLOGICAL AND GEODETIC TECHNIQUES

This section reviews some conventional ground-based techniques used in the seismological and geodetic aspects of earthquake prediction. The discussion is limited to techniques that are relevant to the NASA Geodynamics Program.

3.5.1 Seismological Techniques

Seismometers are used on a worldwide basis for detecting the ground vibrations generated by the seismic waves associated with earthquakes, underground nuclear explosions, and pressure fluctuations in the atmosphere. The interpretation of these recorded vibrations has provided the largest single source of data on earthquakes. Seismology addresses such basic questions as the time, location, and energy release of the detected events. It has been used for making estimates of the faulting mechanism, ground accelerations, source dimensions, stress drop, and other basic parameters of earthquakes. Seismology provides the principal information for determining the density and internal structure of the earth and other solid planets.

The current World Wide Network of Standardized Seismic Stations is capable of detecting virtually all events of body wave magnitude 5 or greater anywhere in the world. The epicenters are usually accurate to better than 25 km, and the depth to the focus can frequently be inferred to about 30 km. The quality and distribution of instruments used worldwide has shown steady improvement. For example, in 1960, most events with body wave magnitudes greater than 6.5 were detected and located. By contrast, in 1973 the lower limit had improved to magnitude 4.8. However, many smaller events are not detected because of uneven distribution of instruments.

In several active areas with local seismic networks, the local events can be located to an accuracy of about 6 km in all directions. The USGS arrays in California show that a dense local network can allow event location to 2 km and magnitude determination down to magnitude 0.25 for all events with epicenters within the network.

If an event is observed at a number of stations well spaced in azimuth and distance, the direction of the initial ground motion at the recording sites can be used to determine a set of two possible fault planes. The actual fault plane can usually be selected from the allowable candidates by geologic and other considerations.

3.5.2 Geodetic Techniques

Geodetic techniques are used to measure changes in the shape of the earth's crust, an activity which has been called "low-frequency seismology." Most older measurements were made with triangulation surveys in which the directions between networks of stations separated by several kilometers were measured. By resurveying the network at appropriate intervals and noting the changes in the relative orientations, deductions can be made concerning slippage across a fault, strain rates, creep, etc. Conventional surveys have a resolution of a few arc seconds, that is, 1 part in 10^5, or about 10 cm over a distance of 10 km.

In the past decade or two, triangulation methods have been replaced by trilateration surveys in which the distances between the network stations are directly measured, usually by laser geodimeters in which a modulated light beam is transmitted from a station and reflected back from another station. Varying the modulation frequency permits a determination of the station separation. These devices have an accuracy of from several millimeters to about 1 centimeter in 10 km. However, fluctuations in the atmosphere cause variations in the light path which introduce uncertainities of about three parts in 10^7 to one part in 10^6, depending on whether the atmospheric density along the optical path is observed by aircraft. Multicolor devices now under development permit atmospheric corrections and improve the sensitivity to about 1 part in 10^7 (for a review, see Levine, 1978).

Strain gauges and creepmeters are also used for measuring the change in distance between two points but in this case the separations are only a few meters. Typically, the measurements involve stretching a wire or metal bar between two buried anchor points. Typical sensitivities are 1 part in 10^5 to 1 part in 10^6. Laser interferometric devices have sensitivities several orders of magnitude better, but improvements are needed in the piers on which the elements are mounted in order to avoid introducing noise into such systems.

Leveling surveys are made over several kilometers to reveal changes in the vertical distance between two points. For relatively short distances first-order leveling surveys have a demonstrated precision of about 1 mm for 1 km of leveled distance, and the error increases as the square root of distance. Systematic errors, unless corrected, can accumulate at a rate proportional to the distance.

For very localized measurements, tiltmeters are used. These respond like bubbles in a carpenter's level to local tilts. Operational tiltmeters have sensitivities in the neighborhood of 10^{-8} radians, but conventional tiltmeters are very sensitive to small-scale geological inhomogeneities. Better results can be obtained with long baseline fluid-filled tiltmeters (Huggett et al., 1976).

Although most of the geodetic techniques discussed above have a formal precision of 1 part in 10^6 or better, the accuracies are often more limited by geophysical noise and very local effects such as thermal expansion of rocks and rain-induced changes in the water table. Further research in developing ground measurement methods is needed. While conventional geodetic surveys are the primary techniques for crustal motion measurements, severe limitations are imposed by the difficulties in maintaining accuracies over long distances and sometimes inhospitable terrain, as well as the cost of repeated surveys over short times.

It seems likely that conventional geodetic surveys and the space techniques will play complementary roles in obtaining the data on crustal deformation in seismic zones that is needed for earthquake prediction research.

SECTION 4

MEASUREMENTS AND MODELS

In the preceding section, the scientific aspects of global dynamics and earthquake prediction pertinent to this plan were discussed. This chapter discusses how space techniques can be used to make the geodetic measurements needed to construct and evaluate global geodynamic and earthquake-prediction models.

These models involve studies at global, regional, and local scales and this chapter is divided accordingly. This organization parallels that of the corresponding parts of the preceding section.

4.1 OVERVIEW

4.1.1 Introduction

In this section we discuss in general terms the types of physical models for geodynamic processes that can be formulated to explain observed crustal motions, giving several specific examples of how geodetic data are actually used in such models.

As is usually the case in the early stages of evolution of a difficult scientific discipline, different models now exist to describe crustal processes, and competing models often attempt to explain the same crustal behavior. When two different hypotheses allow or predict similar crustal movements, it becomes difficult to determine the correct model on the basis of observational evidence. In this case it can be shown that the more precise and the more dense the crustal motion measurements, the better one can handle the problem of lack of uniqueness and select among the hypotheses that describe similar behavior. This need is an important rationale for the implementation of the extraterrestrial geodetic techniques, with their improved accuracy over longer distances, in the study of crustal movement. For further discussion, see Whitcomb (1978).

4.1.2 Areas of Application

Geodetic measurements using the substantial improvement in both long-baseline accuracy and frequency of measurement provided by extraterrestrial techniques, have important bearing on many areas of tectonophysics; for example, volcanism, plate tectonics, and earthquake processes. In this section we discuss some of the relevant applications.

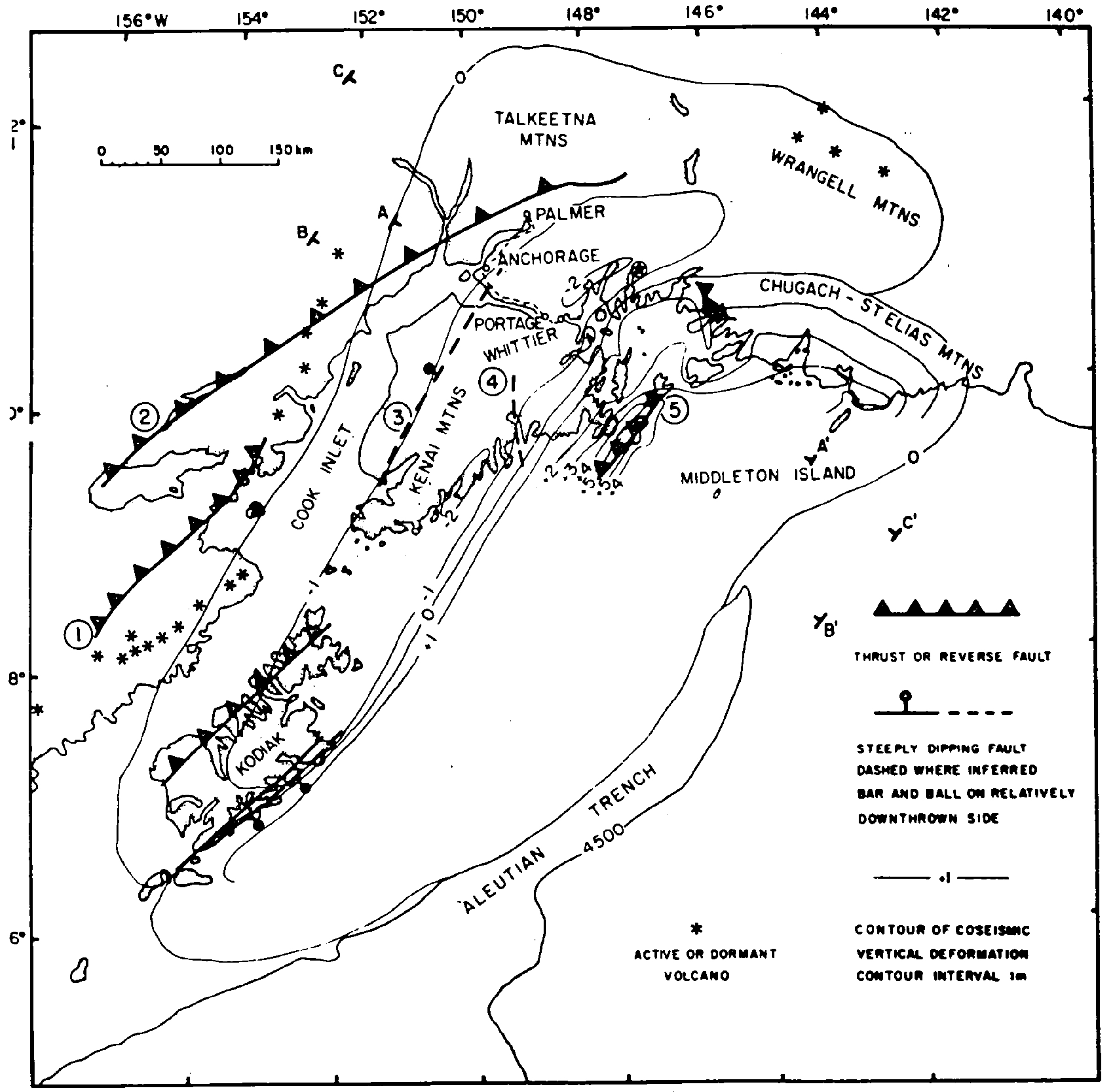


Figure 4.1-1. Coseismic vertical deformation in Alaska following the 1964 earthquake (after Plafker, 1979). Circled star: earthquake epicenter. Fault 1: Bruin Bay; fault 2: Castle Mountain - Lake Clark; 3: Cook Inlet lineament; 4: Kenai lineament; 5: Patton Bay and Hanning Bay (from Brown et al., 1977).

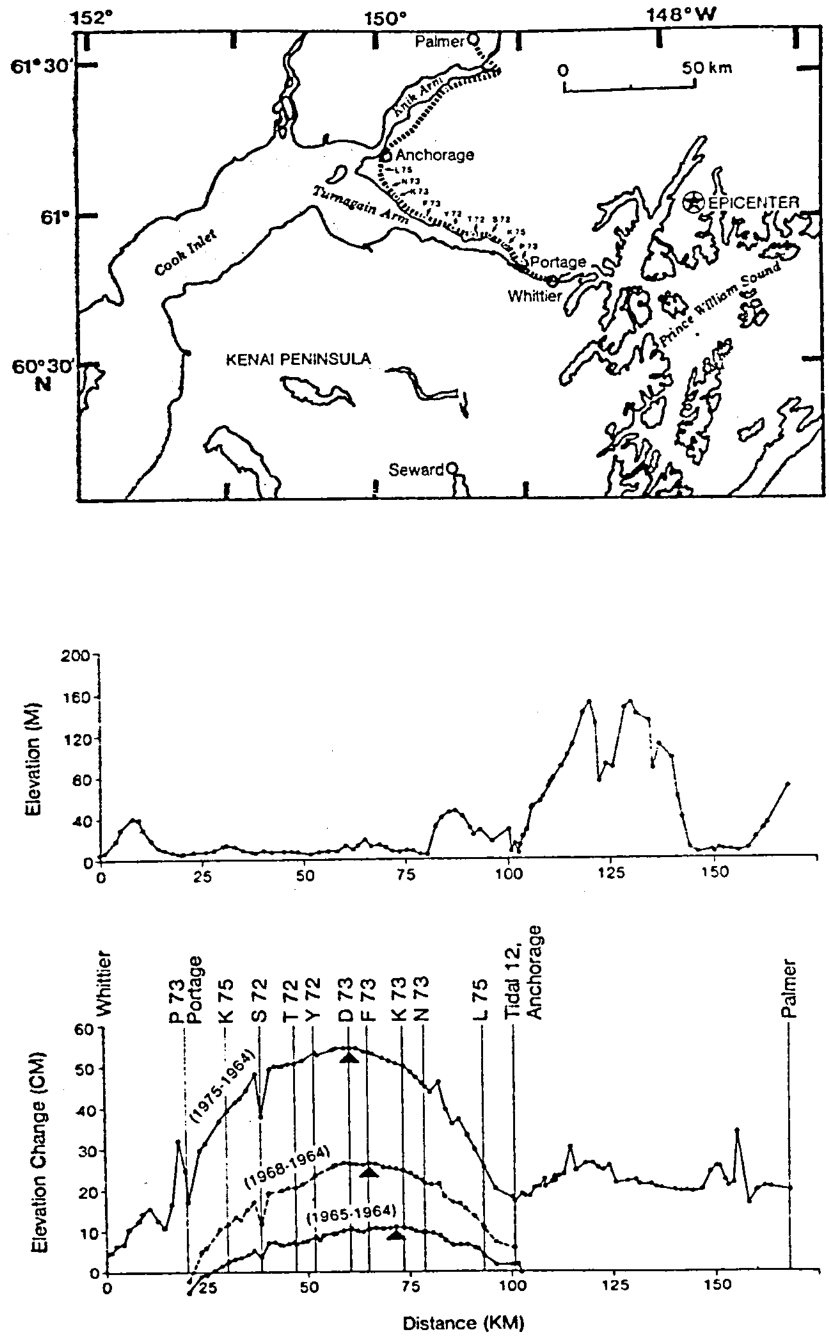


Figure 4.1-2. Uplift following the 1964 Alaska earthquake (from Brown et al., 1977).

4.1.2.1 Earthquakes

Geodetic measurements - including gravity - have been primary tools for the definition of crustal distortion resulting from earthquakes. Among the important economic issues are the flow of water in sewers, water lines, and canals in affected areas. Coastal regions may experience significant modification of harbor bottoms and shallow ship channels, such as occurred in the major 1964 Alaskan earthquake. Deformation during this earthquake exceeded 5 meters (16 feet), as shown in Figure 4.1-1 (Plafker, 1969). Subsequent analysis of gravity and leveling data after the Alaskan earthquake revealed even further post-seismic uplift of 0.55 meters in portions of the region (Figure 4.1-2, from Brown et al., 1977). Investigations like this give considerable insight into the buildup of strain that must be relieved in the next major earthquake in the region. They also may give clues to strain buildup in other similar tectonic regions where earthquakes are imminent (for a review, see Reilinger, 1978).

Other examples of distortion related to earthquakes are the 1959 Hebgen Lake, Montana, earthquake (Reilinger et al., 1977), and the 1971 San Fernando, California, earthquake (Castle et al., 1974). In both of these, premonitory uplift was seen in leveling data gathered years before the earthquakes. Extensive leveling and gravity data were taken there during the 1965 Matsushiro, Japan, earthquake swarm, and analysis of the data provided insight into crustal distortion models that pertain to earthquake prediction (Whitcomb, 1976).

Post-earthquake geodetic data gathered at frequent intervals (weekly or monthly) can be used to differentiate between postulated models that depend on the rate of subsidence of pre-earthquake uplift. For example, one model with water in the crust predicts slow post-earthquake subsidence, and one without water predicts rapid or nearly instantaneous subsidence.

Aseismic slip, that is, slip along a fault surface without the radiation of seismic energy, is currently a topic of intense interest (Kanamori, 1977a). It is possible that a major portion of strain buildup by plate tectonic

motion may be relieved in pre- or post-earthquake aseismic slip at plate boundaries. If this is true, it has an important bearing on estimates of seismic hazard in earthquake-prone regions. Our uncertainty about contemporary motions of plates and their relationships to the time and place of great earthquakes affects long-term earthquake prediction, models of the properties of the crust and upper mantle rocks, and models of the forces that drive the tectonic plates. Detailed measurements of inter- and intraplate motions, correlated with the occurrence of major earthquakes, is an absolute necessity, and extraterrestrial geodetic methods offer the only possibility for such measurements.

A graphic example of the need for horizontal long-baseline geodetic measurements (greater than 100 km) arises from the application of plate tectonics theory to the estimation of recurrence rates of great earthquakes along the San Andreas Fault in California. A typical slip of the San Andreas Fault in the region of the great 1857 Fort Tejon earthquake was a few meters. If we knew the rate of plate motion between two blocks, and were sure that the motion had to be relieved only in great earthquakes, we could estimate how often the earthquakes had to occur on the average. For example, the most recent magnetic anomalies in the oceanic crust (which provide a record of sea-floor spreading on a time scale of hundreds of thousands of years) predict that the motion between the plates on either side of the San Andreas Fault (the North American and Pacific Plates) is about 5.5 cm/year. A typical magnitude 8 earthquake on the San Andreas has a slip on the order of 6 meters. A simple calculation with these numbers gives a rough estimate that a great earthquake must occur on a given segment of the San Andreas fault every 110 years or so. Recent geological evidence implies that the recurrence interval over the last few hundred years in Southern California may be variable, and considerably longer than 100 years (Sieh, 1978). Still, this type of reasoning has been the basis for concern about the southern portion of the San Andreas Fault, where the last magnitude eight earthquake occurred more than 120 years ago (in 1857). However, this reasoning is based on several assumptions, the main one of which is that the plate motion has been constant over this period of time. In reality, plate tectonics can at present tell us only what the average rate has been over a much longer time period, and the present models are inadequate to predict movement over periods as short as a century. The basic question is whether the movement of plates, and the distortion and deformation that accompanies their gross movement, is smooth or jerky.

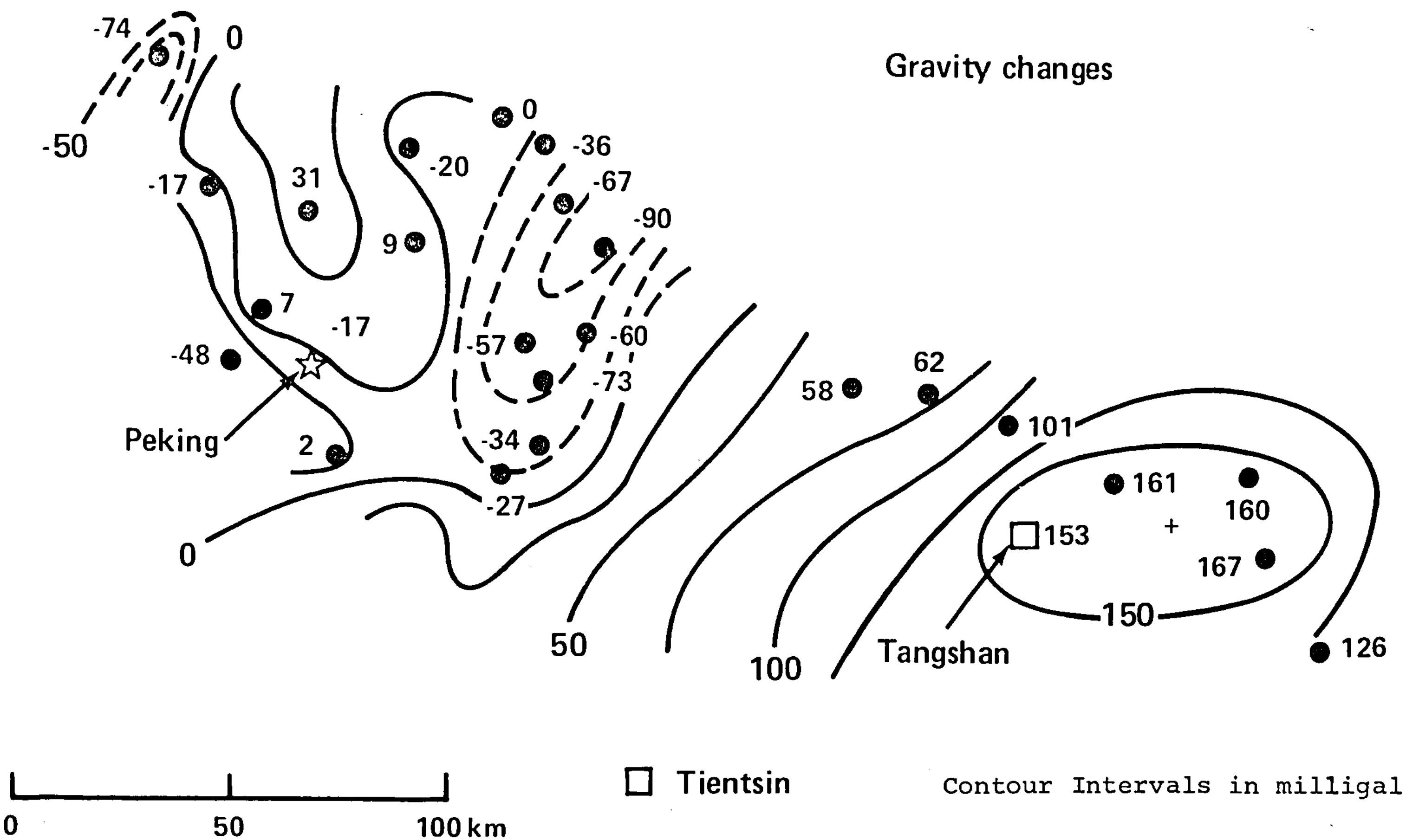


Figure 4.1-3. Changes in gravity from March 1976 to July 1976 near Tangshan, China (from Wang, 1978).

It is known that plate movement is variable in space. For example, the San Andreas Fault in Central California is creeping at a rate of about 2.5 cm/year in a right-lateral sense (Nason, 1971a, 1971b; Burford and Harsh, 1979), although geodetic measurements in this area show a movement of about 3.2 cm/year (Savage and Burford, 1973), a difference that may be explained by the measurement errors. In the "Big Bend" region of the fault in Southern California there are indications from VLBI measurements of right-lateral displacement of about this same amount between points on opposite sides of the fault (Ong et al., 1977). However, recent geodimeter net observations across the San Andreas Fault in Southern California are difficult to interpret in terms of dislocation models of any sort (Savage and Prescott, 1977), and results from the SAFE experiments show a right-lateral movement of about 9 cm/year between the Northern Sierra and San Diego, on opposite sides of the San Andreas Fault (Smith et al., 1979). One of the major contributions of the crustal dynamics program described here will be to measure how the movement across the San Andreas Fault zone is distributed in space as well as time. There is geologic evidence that the entire area of the Western United States may be involved (Hamilton, 1978).

In earthquake research, there is encouraging evidence that geodetic measurements have application to short-term crustal distortion preceding earthquakes. Gravity data from China gathered prior to the 1976 Tangshan earthquake showed significant changes prior to the earthquake. Figure 4.1-3 shows contours of gravity changes between a survey made six months before the event and just before the event (Wang, 1978). Changes up to 150 microgals are seen. It is likely that much of this could be due to elevation changes prior to the earthquake. It would have been extremely valuable to have geodetic data at the same time as the gravity data were taken. The observational schedule for the crustal dynamics program is designed to maintain flexibility to divert the mobile stations to concentrate on areas where anomalous crustal movements are taking place.

Central to all the uses of geodetic data to estimate long-term earthquake hazard, and perhaps short-term earthquake prediction, is the nature of stress and strain buildup within the crust. Much evidence from post-earthquake geodetic data indicates that elastic strains approaching 10^{-4} are sufficient to build stress to the rupture level of crustal rocks. However, an unresolved question is how much of the crustal distortion is plastic in character. Stress

levels in plastic deformation will be less than those for elastic deformation of the same amount. This uncertainty bears directly on the estimates of earthquake recurrence intervals along given portions of a fault system. Measurement of plastic behavior can be made by correlating detailed geodetic data in a distorted region with contemporary stress measurements. Reliable stress measurements are extremely difficult to obtain, but they are being made now in California using over-coring and hydraulic fracturing techniques. The geodetic measurement programs are being coordinated with the programs of stress measurement.

It is important to realize that in order to ensure maximum benefit from long-baseline geodetic measurements, complementary geophysical measurements must be made to resolve uniqueness questions in the interpretation of geodetic data. For example, understanding subsurface processes requires gravity data as well as vertical movement data. Other geophysical measurements may be equally important for correlation with geodetic data for model formulation and testing. It is generally agreed that a practical earthquake prediction system will require multiple geophysical data types observed in both temporal and spatial coincidence in order to give the required confidence in decisions that are sure to have far-reaching social and economic implications.

4.1.2.2 Volcanic Eruptions

Catastrophic volcanic eruptions are among the most formidable and potentially destructive natural phenomena. Rapid and remote monitoring of the deformation of volcanic cones would be useful in studies of these phenomena, especially in conjunction with seismological, gravity, and other geophysical monitoring methods. A recent example was the increase in activity in 1976 of a volcano on Guadeloupe in the Caribbean. Surveying on the volcano itself became very dangerous due to intermittent minor eruptions, yet information was critically needed by scientists who had to make decisions on the probability of a major eruption.

The extraterrestrial geodetic systems provide a hitherto unavailable data type for the study of crustal distortion in such situations.

4.2 GLOBAL MEASUREMENTS AND MODELS - PLATE TECTONIC MOTIONS

4.2.1 Objectives

It is clear from the preceding discussion that the processes causing earthquakes are intimately related to those moving and deforming the tectonic plates. In this section we discuss geodetic observations which might be made by NASA to contribute to understanding global-scale tectonics. Two major questions of global-scale plate tectonics are: (1) what are the present motions of the tectonic plates with respect to one another and with respect to a coordinate system fixed in the earth? and (2) what are the forces or combination of forces that drive these motions? Because of the inherent limitations of ground-based geodetic methods, no direct measurement of interplate motions was possible before the advent of space techniques, except on a very local scale. The space geodesy techniques are suitable for making observations of position and position changes of widely separated points of the earth's surface.

The space-derived methods for position determination yield point measurements. These observations taken alone are inadequate to determine large-scale plate motion. It is necessary to complement such measurements with auxiliary measurements at two scales because a determination that a point on a plate is moving says nothing about the plate as a whole unless we know something about the stability of the plate itself, i.e., whether large-scale deformations of magnitude comparable to the absolute interplate motion are occurring. This implies that a network of observing sites must be established on each plate, and the relative motion of these sites determined. On a smaller scale it is possible -- even likely -- that purely local vertical and horizontal movements may occur and mask the large-scale motion sought. This necessitates operation of local instruments to monitor changes in height, as well as local geodetic surveys to relate the observing site to benchmarks within a few tens of kilometers.

In terms of the major problems discussed at the beginning of this section, we can state the primary objectives of a space-related program of global observations of tectonic plate motion as:

1. To provide a crucial test of the plate tectonics theory, by direct measurement of the plate velocities and directions and comparison with predicted values.

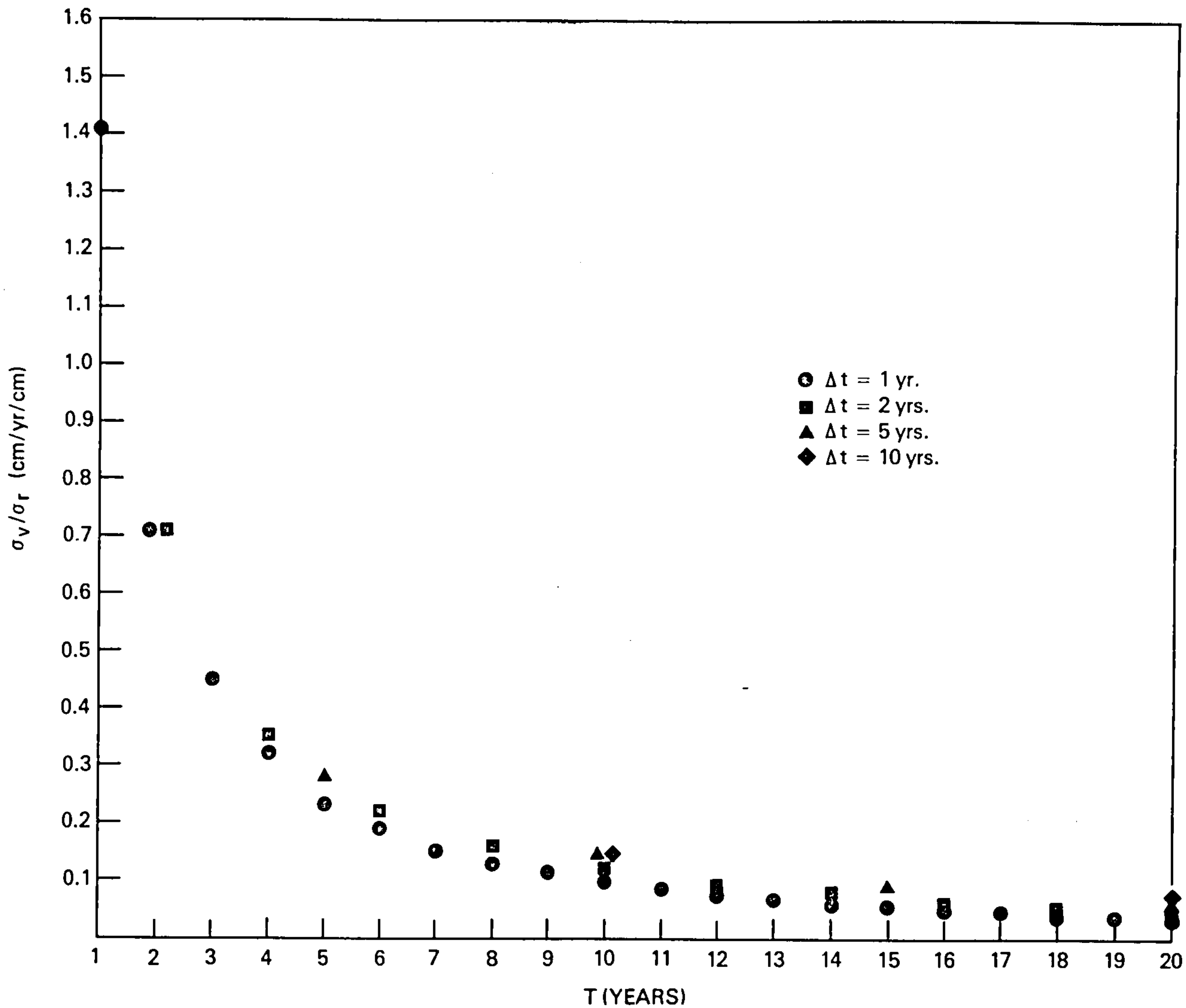


Figure 4.2-1. Standard deviation of velocity determination as a function of time.

2. To determine the motions of the major tectonic plates with respect to each other and with respect to the center of mass of the Earth.

3. To determine the large-scale stability of the plates and monitor their internal deformations.

The interpretation of these measurements of plate motion may lead to working hypotheses about the mechanisms that drive the plates and create internal distortions. If episodicity of the gross inter-plate motion or internal plate deformations are discovered, this should be particularly useful in deriving a model for the plate-driving forces. It should also be noted that monitoring of internal deformation of plates will be useful to conventional geodesy by indicating when local surveys should be re-done.

4.2.2 Space Geodesy Measurements

4.2.2.1 Accuracy Requirements

The accuracy with which the relative velocity between two points can be determined, σ_v, depends primarily on the accuracy in the baseline measurements, σ_r, and the period between the first and last observation, T. For measurements made at time intervals Δt apart and without slowly varying systematic errors, the velocity uncertainty is:

$$\sigma_v = \frac{\sigma_r}{T}\left\{\frac{12\ T/\Delta t}{(1+T/\Delta t)(2+T/\Delta t)}\right\}^{1/2}$$

The standard deviation of the velocity determination is shown as a function of time in Figure 4.2-1. For example, with σ_r = 5 cm and Δt = 5 yr, σ_v = 1.4 cm/yr after 5 years, 0.7 cm/yr after ten years, and 0.3 cm/yr after 20 years.

Some implications of the figure should be noted. First, it is apparent that the most rapid improvements in the interplate velocity determinations come with the first few measurements. For example, the velocity uncertainty, σ_v/σ_r, decreases from 0.71 after two years to 0.33 after four years, an improvement of a factor of two. To achieve a further factor of two improvement would require more than twenty years of continued measurements. However, this is only true if the motion is uniform, which is probably not the case. Nevertheless, episodicity of movement should be detectable on a time scale of two to four years at the 1 cm/yr level.

The figure also suggests that there is little improvement in the velocity determinations with increased frequency of measurement. The data points for the various values of Δt lie relatively close together. While this is true in principle, it assumes a knowledge of the uncertainty in the intersite baseline determinations. In general such knowledge can be reliably obtained only by making repeated measurements at frequent enough intervals to establish good statistical properties in the data set.

Finally, Figure 4.2-1 shows that velocity determinations accurate to better than 1 cm/yr may be possible with a decade of measurements or less, since existing systems permit baseline determinations precise to a few centimeters, and future systems are expected to achieve even better precision. The analysis of errors and detectability of changes in movements will be carefully studied in the early stages of the program being discussed here.

Motions in the interior of plates may be of smaller magnitude (on average) than the interplate motions, and the parameter of particular concern is not so much velocity but strain. Since a strain accumulation of 1×10^{-7}/year is significant in seismic risk analysis (equivalent to a change of 10 cm in a 1000 km baseline per year), and since we are concerned with stability of the region over a 10-year period, we must be able to measure strains of about 3×10^{-8}/year (or 3 cm over 1000 km), which implies relative position accuracies of about 2 cm over distances of 1000 to 2000 km. On the short term there is reasonable evidence that vertical motions are of comparable order to the horizontal, and hence, similar accuracies are required.

4.2.2.2 Strategy

The measurement of interplate motions is based on the concept of relatively rigid lithospheric plates. This concept finds support in the apparent lack of large-scale horizontal motions in the plate interiors.

If it is assumed that the plates are rigid, then measurement at two single points on each plate are required for deducing the translational and rotational motions; in practice, at least three sites per plate should be used in the measurements program to provide internal consistency checks and to minimize problems that sometimes arise from the intersite geometry. We note that in North America and

Europe more stations might be available because other supporting and developmental programs provide valuable measurements. Three sites properly chosen in the interior of the plate could be used for both the interplate ties as well as to answer basic questions of interior plate stability. Although the interest in the United States focuses on the North American and Pacific Plates, the problem is a global one; hence a worldwide network of about 30 sites would eventually be required for a comprehensive program. Because of the advantages of increasing the number of sites, NASA will work in collaboration with teams in other countries to make these measurements. If large deviations from interior plate rigidity are detected, then more sites will be required for those plates than are indicated by this minimum program. This indicates the necessity to maintain flexibility in planning the program beyond the first few years.

The systems to be used for the measurements will consist of both the laser ranging tracking systems (artificial satellites and Moon) and the very long baseline interferometer systems, and will employ both fixed and mobile stations as they become available.

4.2.2.3 Plate Deformation - Networks

We have discussed two global-scale objectives of the crustal dynamics program: relative motion of tectonic plates and deformation of plate interiors. Information on relative plate motion will come from the continuing data acquired by the global network of fixed laser ranging and VLBI observatories, but as we have pointed out, the observatories may be moving with respect to other parts of the plates on which they are located. This is part of the rationale for a study of the large-scale deformation of the plates.

The purpose of establishing sites in the interior of plates from a tectonic point of view is to answer the question of stability or rigidity of the plate, over a time span of, say, 10 years. The observing sites may be subject to local movements which can take place on a time scale of months or weeks. If measurements are made only every year or so, they may miss some information. The ideal situation is one in which observations are made weekly, which is possible at dedicated VLBI or laser ranging facilities. Such near-continuous measurements would also be of interest because they indicate the frequency of measurements required in an operational situation, as well as defining the nature of episodic motions in plate interiors. The Polaris VLBI

stations will provide this frequency of data for North America while obtaining polar motion measurements with a time resolution of a few hours (see Section 4.3).

For this study it is logical to make use of the fixed observatories and the Moblas sites discussed below to the largest extent possible. This indicates that initial efforts should be concentrated on the Pacific, North American, European, and Australian plates. The presence of fixed observatories and a Moblas tracking site on the aseismic and presumably stable Australian continent makes this an attractive location. Fixed VLBI stations at Onsala, Sweden; Bonn, West Germany; and Madrid, Spain, plus Moblas laser pads and several European laser systems will make western Europe one of the best studied regions.

North American Plate Deformation

Despite the fact that many important geological and geophysical ideas have been based on studies of North America and the nearby ocean basins, this continent is an extremely complicated one whose place in the plate tectonics model is not yet clear.

The pre-Cenozoic framework of North America appears superficially rather simple, since there are broad belts of successively younger rocks surrounding an older Precambrian nucleus. The early theory that the continent grew by lateral accretion has given way to the view that the younger rocks were added to the continent by collisions with other plates before the present cycle of plate movement.

The North American Plate is slowly moving away from the Mid-Atlantic Ridge, and the east coast is a passive margin. The western part of the continent is very complex, consisting of a broad belt of active faulting concentrated in the San Andreas Fault System and in the Basin and Range Province between the Colorado Plateau and the west coast. The East Pacific Rise forms part of the boundary between the Pacific and North American Plates; it runs northward from the Rivera Triple Junction into the Gulf of California, beyond which the San Andreas Fault System forms the plate boundary until it terminates at the Mendocino Triple Junction off the coast of Northern California. It has been speculated recently that in Southern California the actual plate boundary at depth is east of the San Andreas Fault, a view supported by seismo-tectonic studies in Southern California (Johnson, 1977). A complex system of ridges, spreading centers, and a subduction zone forms the plate boundary northward into Alaska.

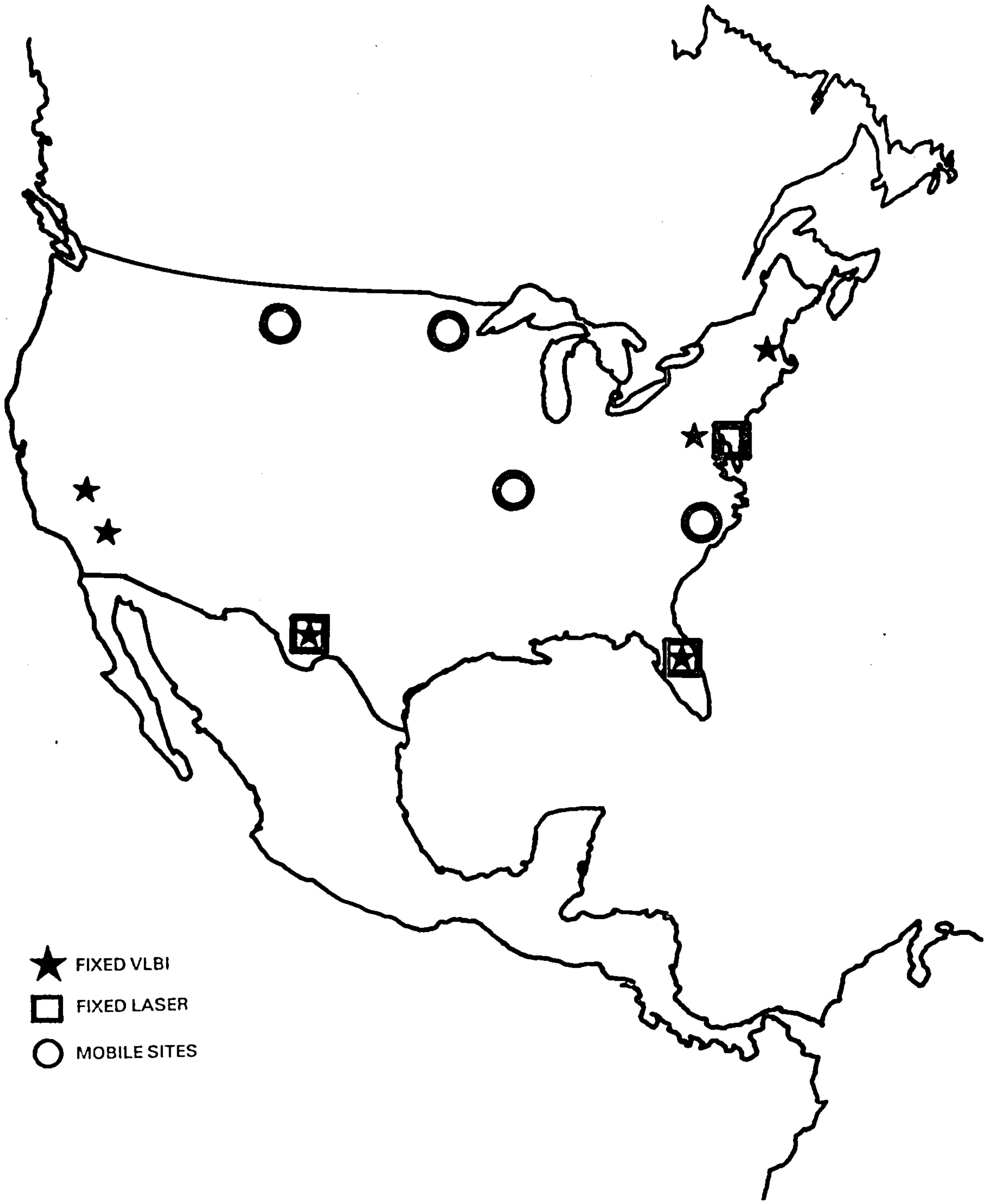


Figure 4.2-2. Proposed arrangement of fixed and mobile laser and VLBI sites for the study of North American plate deformation.

Atwater (1970) explained the tectonics of the North American Cordillera as the result of interaction between the North American Plate and various eastward moving plates in the Pacific Basin. Nur and Ben-Avraham (1977) recently hypothesized that North American has overridden fragments broken off the Antarctic Plate. Dickinson and Snyder (1978) explain many of the features of the San Andreas Fault System, and suggest the existence of a subducted slab in the western part of the United States, left from the time that the North American continent overrode the East Pacific Rise.

The Basin and Range Province is a very broad zone of northwest-southeast shear and crustal extension. There is little doubt that the western part of the United States is undergoing extension by movement on a large number of faults as far east as the Rio Grande Rift in New Mexico and West Texas.

As we pointed out in earlier sections, measurements of crustal deformation made to date in California are only in rough agreement with the 5.5 cm/yr relative motion of the Pacific and North American Plates in this area predicted by the model of Minster et al. (1974) and Minster and Jordan (1978). In some parts of the San Andreas Fault there is no present movement at all, while in other parts the fault is creeping without significant earthquake occurrence. Long-term geologic and classical geodetic measurements in central California show only 3-4 cm/yr movement on the San Andreas Fault. A major question for earthquake prediction in this area is the nature of the distribution of strain (and its changes) along the plate boundary. This, as we have discussed before, is the basis for a regional strain study in this area, extending across the Basin and Range Province.

For measurements of the gross deformation of the more stable eastern part of the North American Plate, we will use a combination of fixed observing sites and a few mobile sites. Figure 4.2-2 shows the arrangement proposed. In addition to the fixed observatories at Stalas, Haystack, NRAO, and McDonald, mobile sites will be located on the mid-Atlantic coast, in Wisconsin or Minnesota, in central Montana, and in southern Missouri - the last of which will provide a reference point for crustal deformation studies in the seismically active area of southeastern Missouri. It is obviously desirable to have several sites in the Canadian shield in Canada, as well as a site for checking on vertical movement in the Appalachian area. Position determinations will be made at the mobile sites once per year.

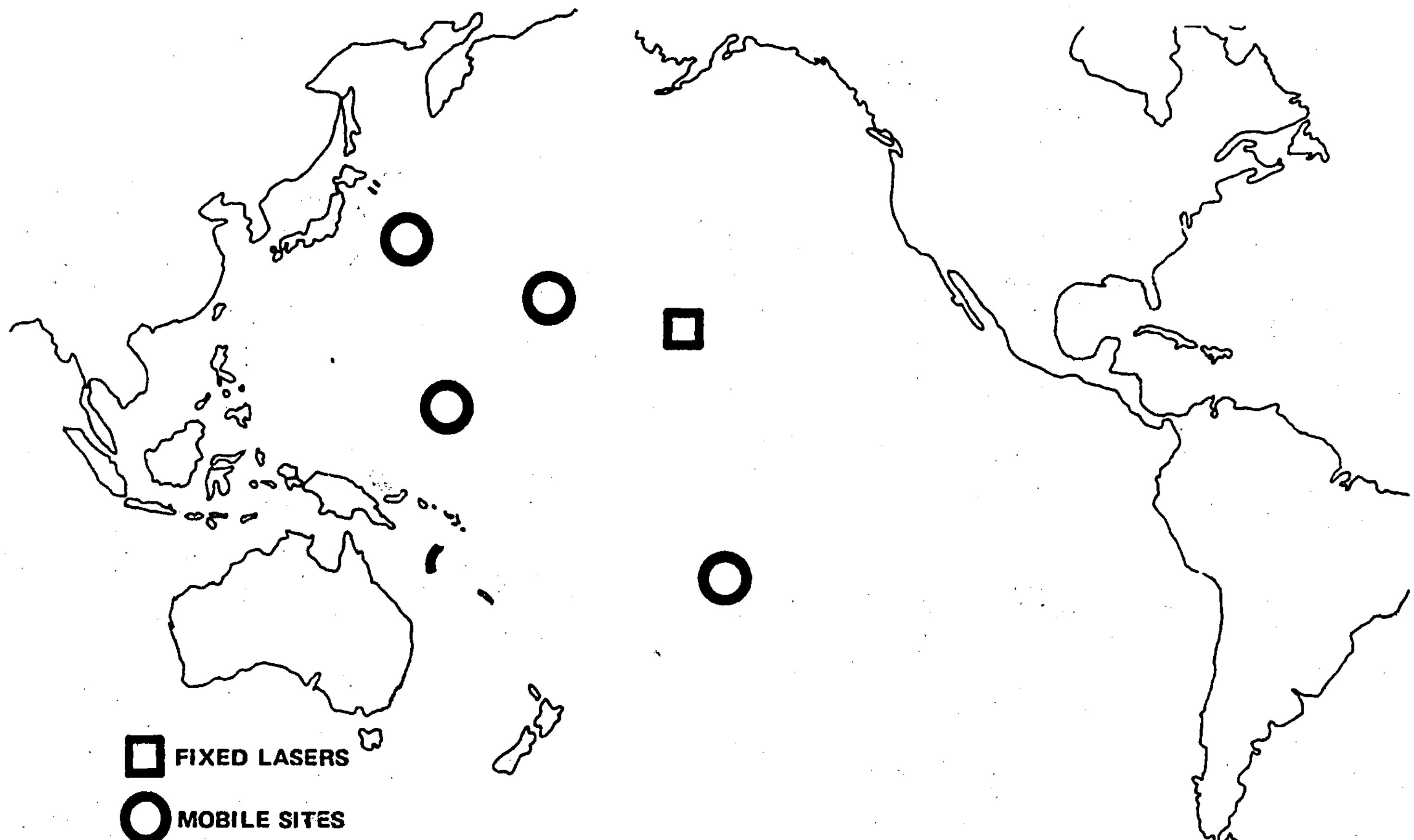


Figure 4.2-3. Proposed arrangement of observing stations in the central Pacific for the study of Pacific plate deformation.

Pacific Plate Deformation

Figure 4.2-3 shows the proposed arrangement of observing stations in the central part of the Pacific plate. Haleakala will be the base station. The Moblas sites at Kwajalein and American Samoa will begin acquiring data in 1979. New sites at Tahiti or at Midway Island or the Marianas would provide a strong quadrilateral in the interior of the Pacific plate. Alternatives could be chosen if Tahiti or Midway Island present operational difficulties: for example, Wake to the northwest, Pitcairn Island, or a site in the Marquesas to the southeast.

Australian Plate Deformation

Until recently, Australia was thought to be part of a large plate that included India and the eastern Indian Ocean (Minster et al., 1974). Recent studies of seismicity on the Ninetyeast Ridge (Stein and Okal, 1978; Minster and Jordan, 1978) and other geophysical evidence suggest that this plate is probably divided at the Ninetyeast Ridge, with the Indian segment moving northward into Asia more slowly than the Australian segment is being underthrust at the subduction zones to the north and east. The paleohistory of the Australian continent and the Tasman Sea is complex, but at the present time Australia proper appears to be moving fairly rapidly northeastward and away from the Southeast Indian Rise that passes south of it.

The continent is relatively aseismic. Small earthquakes occur in a rift zone extending northward from Adelaide on the south coast, and there is persistent activity in the mountainous areas southwest of Canberra. There is no evidence of active major fault zones at this time.

Two laser facilities are located at Orroral Valley, near Canberra (an SAO station and a lunar laser ranging station built by the Australian government). There is also a DSN station at Canberra and a Moblas tracking site located at Geraldton, on the west coast north of Perth. All of the lunar laser ranging stations will be important parts of the worldwide polar motion system, and the detection of the relatively rapid movement of Australia with respect to the Pacific plate will be one of the most interesting early results of the NASA Crustal Dynamics program. It is therefore desirable to monitor the stability of the Australian plate.

This can be done by re-occupation of the Geraldton site and other sites in the central part of the continent, once a year. For logistical reasons, Alice Springs, Adelaide, and Darwin are the logical sites. Figure 4.2-4 shows the arrangement of these stations.

Western Eurasian Plate Deformation

The three existing VLBI stations at Onsala, Sweden; Bonn, W. Germany; and Madrid, Spain, provide a good North-South configuration for measuring deformation of the western part of Europe. The future addition of a VLBI station in England would make a strong quadrilateral in Europe. Laser sites include those in Germany, France, the Netherlands, and Greece. The observational program for this area is part of the program being developed by the European Space Agency (see Section 6.8).

4.2.2.4 Interplate Networks

Figure 4.2-5 shows the VLBI and laser sites which together will provide the network for studying interplate motions between selected plates. For measuring baselines between the North and South American Plates, the separate VLBI and laser subnetworks are inadequate. However, the combined network tied together by establishing a laser station at the VLBI site in Brazil can accomplish the required measurements. For measuring the Pacific/North American Plate motion, the three or four mobile sites established on Pacific islands for measuring the Pacific Plate deformation will be employed along with stations in the continental U.S. and the laser station in Hawaii. Additional new VLBI stations in Hawaii and Alaska are desirable.

VLBI and laser stations can be used to establish ties between the North American Plate and Europe. The Massachusetts-Florida-Alaska-Sweden-Spain-Germany configuration provides strong ties among these VLBI sites. Laser ties to Europe can be accomplished through the Moblas site at Madrid, the German station at Wettzell, the French station at Grasse, and a Netherlands station at Noordwijk. Another possible cooperative site in Europe is at Athens, Greece - an adjunct station of the SAO. The closeness of the European sites makes them useful for studying the internal stability of this part of the Eurasian Plate.

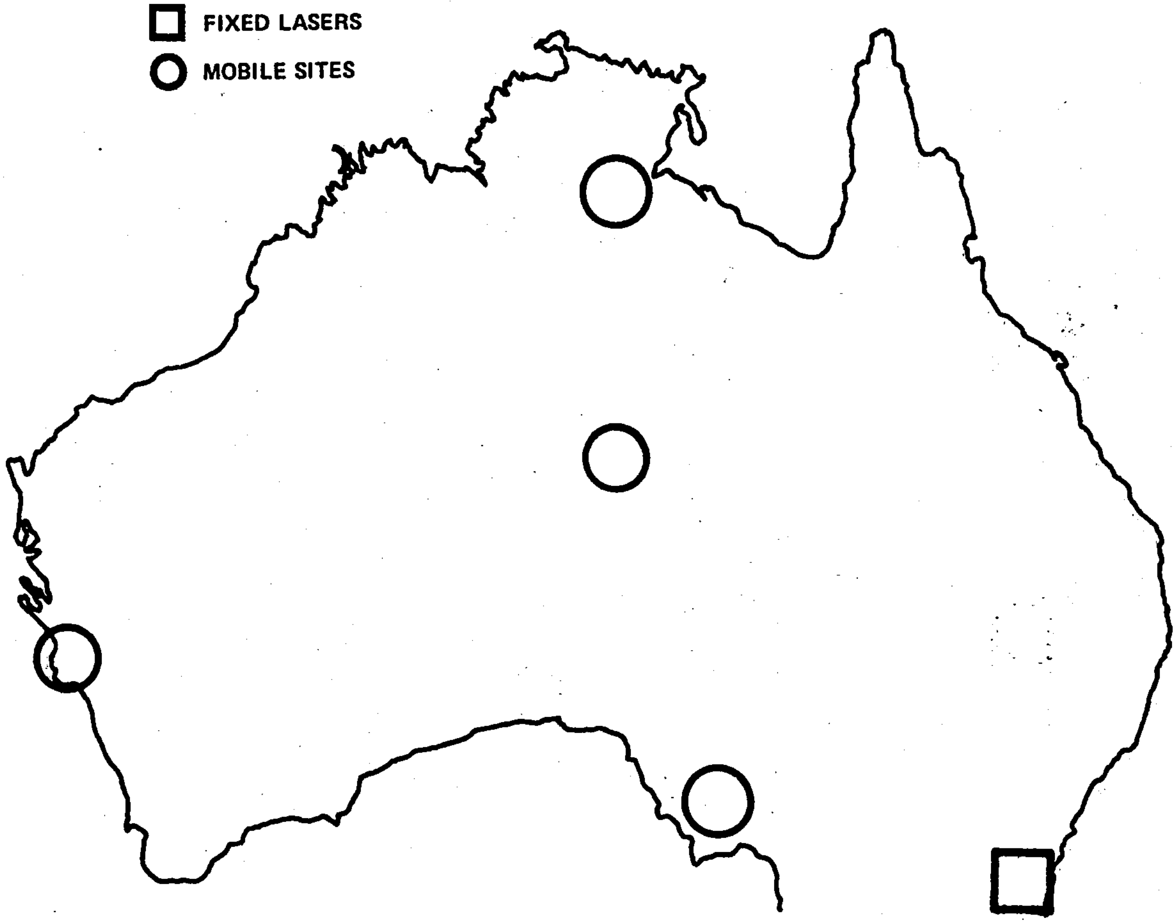


Figure 4.2-4. Proposed arrangement of stations for study of Australian plate deformation.

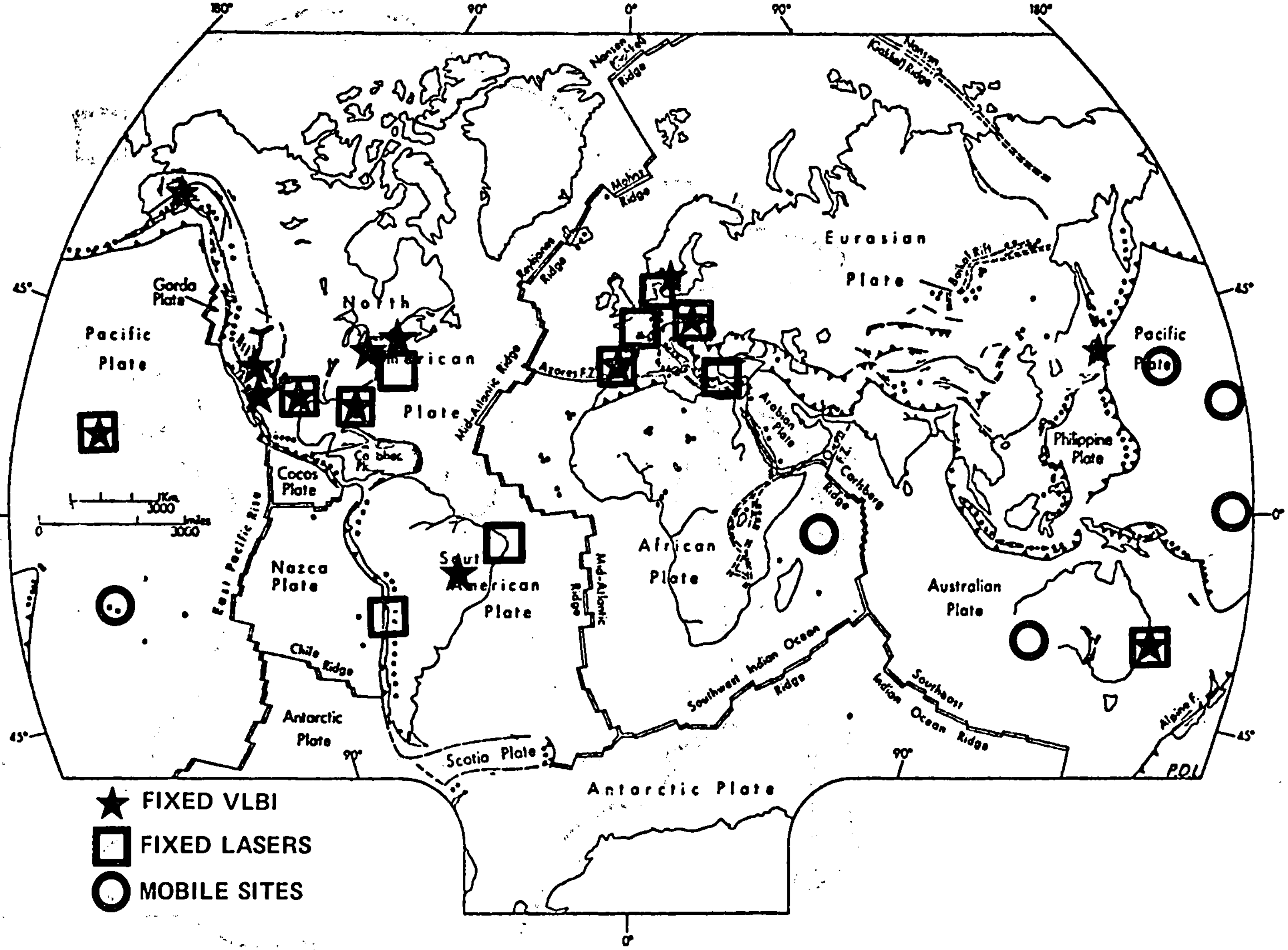


Figure 4.2-5. Network of VLBI and laser sites for global study of plate motion.

As pointed out above, three laser stations in Australia will provide a tie between Australia and the Pacific. Observations in Japan and on offshore islands in the Pacific will provide similar ties between Japan and other plates.

4.2.2.5 Frequency of Measurements

In a noise-free situation, the interplate velocities and their time variations could be measured by observations taken once a year. Ideally all the interplate measurements would be made simultaneously in the framework of permanently operating observatories. This framework must be augmented by an observing program using mobile VLBI and laser ranging stations. It will be advantageous to concentrate the mobile systems on two adjacent plates at a time and perform most of the interplate and intraplate connections during the same period. Subsequently, the mobile station on one plate (or both) will move to another; and so on, until all sites have been occupied.

Plate motion and deformation measurements are particularly important around the circum-Pacific belt. Movements in these regions may affect the earthquake hazard in California and this region is given special consideration in the program.

The length of stay of the mobile systems on a site depends on a number of factors, such as the geometric strength of the line (determined by its orientation and length), and for the lasers, on the weather and weather patterns.

The length of occupation of either the VLBI or laser system will also be influenced by the number of sources or satellites that can be used. A comprehensive catalogue of radio source positions is therefore essential, and the availability of more Lageos-type satellites could shorten the length of occupation of the laser tracking sites. For a discussion of the planning parameters used in the NASA program, see Section 6.

4.2.2.6 Coordinate Systems

Coordinates derived from laser tracking of the moon and artificial satellites are defined by the center of mass of the earth and the earth's angular momentum vector. The

solutions are either "dynamic" (that is, coupled to the deduced orbital motions of the earth, moon, and the satellite) or "geometric", relying on simultaneity of measurements from two or more sites. Observations made using VLBI techniques relate the orientation of the earth's axis to a coordinate system which is fixed in space and defined by the adopted coordinates of the quasar radio sources. The VLBI observations are geometric in nature, and the station positions are relative.

Satellite and lunar laser measurements provide both the distance from the rotation axis and the plane through the center of mass normal to the axis (i.e., the equator). Thus these techniques differ from VLBI in their coordinate systems, and provide uniquely different measurements. For example, possible movements of the lithosphere relative to the earth's center of mass parallel to its rotation axis (due to seasonal atmospheric effects, for example) can only be observed with laser ranging systems, while VLBI permits an inertial determination of spin decoupled from lunar and solar effects.

4.2.3 Supporting Measurements

4.2.3.1 Gravimetry

If the measurements between points on the earth's surface are to be properly interpreted, it is essential to know whether vertical movements have taken place at a site between successive occupations. The monitoring of some sites by gravimeters which have long-term stability could provide important data for deducing vertical motions, although the gravimeter is also sensitive to changes in the position of the earth's center of mass, atmospheric pressure changes, changes in ground-water level, and density changes due to strain accumulation at depth, in addition to true elevation changes. At the General Assembly of IUGG at Grenoble in 1975, the International Association of Geodesy adopted Resolutions 16 and 19, which call for the establishment of numerous absolute gravity stations throughout the world for geodesy and geophysics. Absolute gravity meters are being developed by several organizations in the U.S. and abroad, and this program should take shape within the next few years.

Cryogenic gravity meters are being developed under the present NASA program, and are capable of achieving centimeter stability over a period of one year (Warburton and Goodkind, 1973). If such gravimeters were deployed at some of the fixed VLBI and laser sites and most of the pads for the

mobile systems, they could provide data on global vertical motions and corrected coordinates for the analysis of the data from the space systems. The only alternatives are periodic re-leveling using conventional methods or determination of absolute gravity at the station sites. The technique of segmented leveling to relate elevation at a site to the neighborhood over distances of a few tens of kilometers appears to be adequate for this purpose.

In North America, recommended sites for cryogenic gravimeters in support of a global plate motion program are GSFC, McDonald Observatory, San Diego, Haystack, and Goldstone. In general, at least one system should be established at each of the principal tracking sites on the other major plates. The gravimeters will also monitor the phases and amplitudes of earth tides, correction for which is required in the data analysis. Cryogenic gravimeters are already installed at the San Diego (Otay Mt.) and GSFC (Greenbelt, Maryland) laser sites.

4.2.3.2 Local Geodetic Measurements

Local geodetic surveys will be required around all fixed and mobile sites to ensure that any local horizontal movement of the site can be accounted for prior to using the measurements for estimating plate motions. A small 10 to 20 km network of points near the sites needs to be established for horizontal and vertical control. Any known faults in the region that could be active should be monitored. This work has been initiated at McDonald, Ft. Davis, Haleakala, and Haystack Observatories, and at the Goldstone, San Diego, and Quincy sites in California.

The TLRS can be used to range on ground targets (Silverberg, 1978), so the necessary ground surveys may be possible at TLRS sites using the radial line method developed by NGS (Carter and Vincenty, 1978). Each site should be related to the nearest first-order geodetic control by a first-order survey and to a tide gauge where possible.

4.2.3.3 Seismic Measurements

If earthquakes should occur close to a site it will be important to be able to determine the epicenter and magnitude accurately in order to evaluate the possibility of displacement at the observing site. Thus seismometers and tiltmeters should be installed at those sites at which a modest

earthquake risk exists. Further, all sites should initially undergo a seismic survey which would entail installing a seismometer for a limited period of time to assess the overall seismicity at the site and to identify any active faults. This procedure should be repeated every few years. At McDonald and Haleakala Observatories this kind of installation has already been started and at the San Diego and Quincy site similar measurements are carried out every two years.

4.2.3.4 Geologic Studies

An understanding of the surficial and structural geology of the sites will be important in the interpretation of the measurements and particularly in the understanding of any irregularities in the results. Preliminary site selection surveys of the area will be required for determining the most suitable locations, although geological factors are probably less important than accessibility, availability of power, etc. The compilation of a detailed geological picture of the local area, especially in terms of proximity to recent faulting, is needed for each of the sites.

4.2.4 Modeling Program

4.2.4.1 Plate Motions

The measurement of intersite vectors by space geodetic techniques will be used to answer some basic questions about plate tectonics. Models of relative plate motions derived from the measurements will be compared with those derived from historic geologic data, magnetic data, and other information to compare contemporary motion with longer-term averages. The space data will also be used in conjunction with the plate deformation studies, and models of plate motion may be developed which include both the rotations of the plate on the surface of the earth and their present large-scale internal deformations.

Detailed modeling of the plate motions and deformation is also important in planning the observational program. We anticipate that unexpected discoveries will be made during the observational program which will make it necessary to revise and alter the initial measurements plan.

It is possible to make a quantitative analysis of the resolvability of the relative plate motions for any network of observatories, using only the site positions and estimates of measurement accuracy. This will be done during the initial stages of the project to predict the accuracies expected for plate motion determinations and to identify critical station locations which should be added to the network.

4.2.4.2 Gravity Field

Whether or not mantle convection is the dominant plate-driving force, there must be a return flow in the asthenosphere as subduction occurs, and viscous drag on the underside of the lithosphere undoubtedly influences plate motion and deformation.

There is a large body of literature on mantle convection, which is at present a subject that is not well understood. Many numerical and laboratory studies have been carried out, but the relevance of many of these to the real earth is questionable.

Convection in the mantle is very difficult to study directly. Active volcanoes have been hypothesized to be due to upwelling of columns of hot material from deep in the mantle (hot spots). These provide geological clues to the petrology and geochemistry of the mantle. Observations of surface heat flow shed some light on lateral temperature distribution within the earth. Seismic observations suggest that lateral inhomogeneities of a few percent may exist, but the way velocity information is averaged along seismic ray paths makes this method difficult to apply to the study of the nature and extent of convection. The broad variations in oceanic topography imply some structure at depth. The real questions are the nature and amount of inhomogeneity in the mantle, the extent to which the flow is time-varying, the relative roles of initial and radioactive heat, and the extent to which the lower mantle flow is decoupled from upper mantle flow due to phase transitions and/or composition gradients (Richter and Daby, 1978).

The most promising approach to the problem of mantle convection appears to be the detailed study of the earth's gravity field over the oceans and land areas. This can be done by gravity meters, but more rapidly and inexpensively

using satellite altimetry over the oceans (as from GEOS-3 and Seasat-A), satellite-to-satellite tracking, and by laser tracking of low-altitude retroreflector-equipped satellites. The basic idea is that the fine structure of the gravity field reflects variations in the density distribution within the earth. Thus the presence of convection cells in the mantle should cause anomalies in the gravity field.

The continual refinement of mantle models using all types of data is a major aspect of the program of plate tectonics modeling. Detailed modeling of ridges, subduction zones, and continental margins from altimetry and surface gravity are already providing insight into the structure of the crust and lithosphere, and future work promises even greater knowledge of these mantle processes.

Work has been done for the last decade to develop an instrument for measuring the gradient of the earth's gravity field from orbital altitudes. Several such gradiometers have been constructed and tested, but none appears to be ready for use in satellites within the next few years.

4.2.4.3 Magnetic Field

Information on long-wavelength magnetic anomalies will be acquired by Magsat, a dedicated magnetic field mapping mission to be launched in 1979. This data set will be analyzed along with gravity field mapping and ground-based geological and geophysical surveys to study crustal dynamics in both continental and oceanic areas.

Continued observations of the magnetic field at intervals of about five years will provide information for studying secular variations and the long-term decay of the main geomagnetic field.

4.2.4.4 Tidal Models

Tides in the solid earth and ocean affect the measurement of positions and polar motion because they perturb the station position by a few tens of centimeters with periods near 12 and 24 hours, and because for satellite laser ranging, the orbit of the spacecraft is perturbed. In principle it is possible to derive the body tide at the station from the VLBI and laser data. This has been accomplished with VLBI

data from which the Love number h was derived (Robertson, 1975). The body tide and its perturbation due to ocean loading can also be inferred from gravimetric measurements taken at the site. This assumes a value of h, which is reasonably well-known, and probably adequately models the tidal movement at the station.

The ocean tides and the gravity tide produced by the physical distortion of the earth (body tides) perturb the orbit of satellites (Lambeck et al., 1974; Smith et al., 1973). Instead of the characteristically diurnal and semi-diurnal tidal periods that we see on the earth's surface, the satellite perturbations have periods ranging from about 10 days to a few years. The analysis of the satellite perturbations can be used to estimate amplitudes and phases of components of the ocean tides (Lambeck et al., 1974; Felsentreger et al., 1976) and to infer the deceleration of the moon in its orbit (Goad and Douglas, 1977). Some spatial harmonics of the ocean tides can be determined with high accuracy by this method.

The measurement of solid body tides at tracking sites can also provide information on the ocean tides by giving estimates of the loading effect caused by the ocean tides. This information will be a by-product of the NASA program's data reduction for geodynamics purposes. Such measurements at many points worldwide can act as a constraint in the continuing development of ocean tide models.

The development of a good model of the combined earth and ocean tides is also necessary for precise orbit determination. This model can be derived from the analysis of the orbit perturbations of a number of spacecraft over a period of a few years. The modeling of the tidal perturbations on those spacecraft (such as Lageos) to be used in the measurement of plate motion and polar motion is particularly important, since many tidal periods are very long and can be absorbed into the recovery of, for example, polar motion unless carefully modeled.

4.3 GLOBAL MEASUREMENTS AND MODELS - EARTH ROTATION AND POLAR MOTION

4.3.1 Objective

A primary objective of this portion of the NASA program is to make highly accurate measurements of earth rotation and polar motion. As pointed out in Section 2.2.1.2, such motions are intrinsically important in the study of global dynamics, and they must be accounted for in the precise position determinations that are the major product of space-related geodynamics research. There may be an important, although poorly understood, connection to earthquakes.

4.3.2 Space Geodetic Measurements

4.3.2.1 Accuracy Requirements

Considering first the possible coupling between earthquakes and excitation of the Chandler wobble, the calculated variation of the pole of rotation due to the largest of earthquakes is estimated to be a few tens of centimeters at most. The effect diminishes rapidly as earthquake magnitude decreases. Thus if changes in the center of rotation of the pole position caused by earthquakes of magnitude greater than 7.5 are to be detected, positional accuracies of the pole at the 5 cm level or better are required. For this purpose, averaging of about one day is an adequate time resolution.

For investigations of possible high-frequency phenomena such as diurnal perturbations of the pole due to resonances in the core, time resolution of 12 hours is needed. The magnitude of these effects is generally unknown, but it may be of the order of 10 cm and therefore requires measurements of similar accuracy.

In general, seismic effects are not expected to show up in the measurements of earth rotation (length of day) since they do not significantly affect the earth's maximum moment of inertia. Changes in length of day are correlated with zonal winds and seasonal effects in the atmosphere (Lambeck and Cazenave, 1976). However, the measurement of earth rotation is coupled to polar motion and in most circumstances is a by-product of the observational data. An accuracy objective of $\pm$ 0.1 msec is recommended, which is comparable to a polar motion measurement of about 5 cm.

The objectives in measuring the secular motion of the pole are to ascertain with confidence its existence and vectorial motion (if any). Yearly positions for the mean pole will be readily derivable from regularly determined pole position data averaged over several days. If the position of the pole is derived with a precision of Δr and if we assume the motion of the pole is essentially circular, the uncertainty of the yearly mean position is approximately $\Delta r(2/n)^{1/2}$, where n is the number of measurements in a year. If measurements are made every 5 days with an accuracy of 10 cm, the yearly mean position would have an accuracy of $10/(36.5)^{1/2}$, or about 1.7 cm in each coordinate.

4.3.2.2 Strategy

Because the movement of the pole of rotation and the movement of an observing station due to plate motion are indistinguishable at any one station, the system of stations used to monitor earth rotation and polar motion must also be capable of determining relative movements between stations. The aim of the "tracking" network is to determine the point about which the network is rotating, averaged over a time period of perhaps 12 hours to 5 days. If from one averaging period to the next the relative locations of the stations change, it must be determined from the same or supporting data which of the stations moved and which did not in order for the polar motion to be determined. Fortunately, the motion of the stations due to plate motion and other deformations is small (a few centimeters per year) compared to polar motion. However, as indicated in the previous section, any changes in station position will be important in deriving the secular motion.

The optimum network of stations needs to be developed across several tectonic plates and should circumscribe the pole to achieve uniformity of measurements. For example, measurements only from stations on the North American Plate might be able to derive polar motion but would not be able to separate the secular motion from their own tectonic motion unless tied to a global plate motion network. The measurement of polar motion is inextricably tied to the measurement of plate motion, requiring as many stations as possible common to both networks.

The minimum number of stations required for measuring polar motion is two satellite or lunar laser systems separated by approximately 90 degrees, or three VLBI stations oriented so that two of the baselines are approximately perpendicular. This, however, is a minimum that is probably not practical

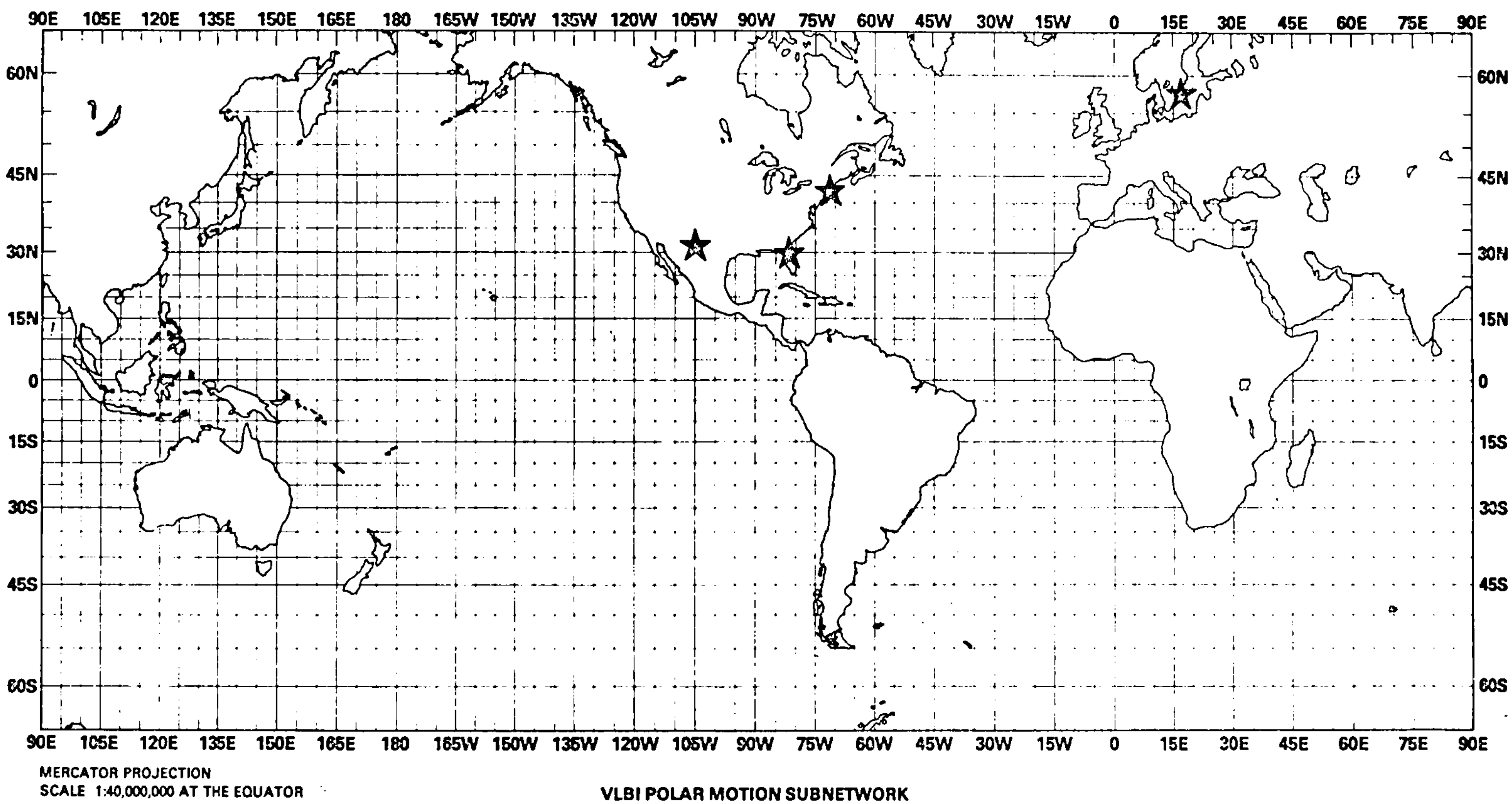


Figure 4.3-1. Planned National Geodetic Survey network for monitoring polar motion (Polaris).

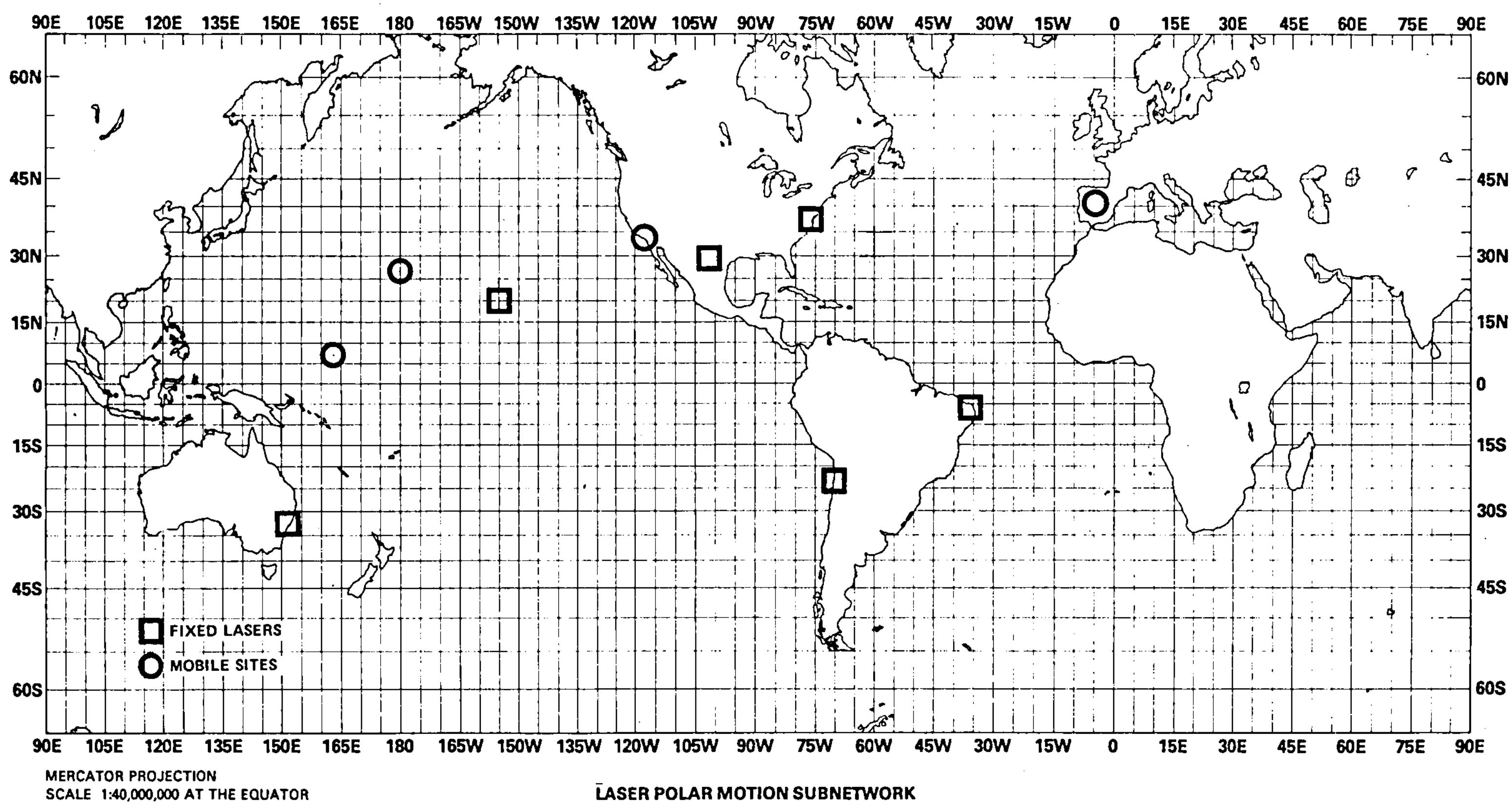


Figure 4.3-2. Laser polar motion subnetwork.

because it fails to take into account instrumental failures or weather problems. More realistically, a minimum of four VLBI or six laser stations would constitute a reliable and useful network. Polar motion stations need to make regular measurements and therefore must be fixed, permanently operable systems. They thus differ from plate motion stations which in many cases can be mobile and probably do not require continuous operations. A network of VLBI polar motion stations operating continuously can determine intersite distances simultaneously with polar motion and earth rotation changes. Thus, such a network can be effective both as a polar motion network and as a part of a plate motion network.

4.3.2.3 Network

Both lasers and VLBI systems can in principle be expected to provide measurement of polar motion and earth rotation at the required accuracy level in the near future. However, because they are measuring in different reference systems, have different systematic errors, and make different basic measurements, it is essential to validate both techniques in an operational mode for at least several years. Indeed, because of the differences already mentioned it can be argued that ultimately a combined network with some common sites will be the strongest system.

Figure 4.3-1 shows the planned NGS VLBI Polaris network of three stations (in Massachusetts, Texas, and Florida), augmented by a station in Sweden (Onsala). This four-station network of fixed VLBI stations is part of the combined laser/VLBI network for measuring plate motion and will therefore be strongly tied together (Carter and Strange, 1979).

Figure 4.3-2 shows the laser polar motion subnet of eight satellite stations and three lunar stations. The satellite stations are at Madrid, Spain; San Diego; Greenbelt, Maryland (GSFC); Kwajalein, American Samoa, and the three SAO sites. The lunar tracking sites at McDonald Observatory in Texas, Haleakela in Hawaii, and Orroral Valley, Australia, will provide independent estimates of polar motion. Since these sites will also track satellites (Lageos), the two networks will be tied together. In addition, all other fixed laser and VLBI sites will contribute to the determination of polar motion and earth rotation, provided that they are operated continuously.

4.3.2.4 <u>Frequency of Measurements</u>

Polar position measurements should be made continuously and averaged over 5 days for direct comparison with the present classical techniques, but taken at shorter intervals for analyses of possible association of crustal deformation or earthquake occurrence with polar motion. Every attempt should be made to collect and use homogeneous data sets both by the VLBI and laser techniques in order to minimize changes in the systematic errors. It is important that stations committed to the measurement of polar motion continue to be operated for an extensive period. It is also important to relate these data sets to the existing body of observations using classical methods.

4.3.2.5 <u>Coordinate System</u>

The coordinate system of the polar motion derived from either VLBI or laser tracking networks is defined by the locations of the stations and their known motion. If the relative locations are known and do not change, then the polar motion can be described by any arbitrary coordinate frame that correctly reflects the relative locations of the stations. The absolute intercomparison of the VLBI and laser polar motion results is, however, only possible if the two networks can be tied together directly or through at least three other common stations. Intercomparisons of changes in pole position can be made relatively if the station locations are stable relative to each other.

If the observations indicate that the geometric relationship between the sites has changed, the station coordinates would need to be known in an independent reference system in order to separate station movement from the polar motion. For VLBI this is accomplished because the station positions are known in an inertial reference system. For the satellite laser system the same referencing of the coordinates to an inertial reference frame can only be done through long-term monitoring of the orbit of high satellites such as Lageos or the Moon. For this to be possible the precession and nutation of the earth in inertial space must be assumed or observed by VLBI or lunar laser ranging. At present, it is thought that no more than five pairs of nutation terms are uncertain at the 3-10 cm level, and the geophysical effects which cause the uncertainty are under active investigation by M. L. Smith and others.

4.3.3 Supporting Measurements

4.3.3.1 Gravimetric

For day-to-day monitoring of polar motion and position at the few centimeter level, the most important in situ measurement is the station tidal motion that must be taken into account in the data analysis. Cryogenic gravimetric measurements can provide some information on vertical changes, and absolute gravity measurements can also be made to detect motion of the solid earth with respect to its center of mass (see Section 4.2.3.1).

4.3.3.2 Local Geodetic

Local horizontal changes over intermediate periods of about a year should be monitored at the sites by regular surveying. Although it is possible, in principle, for the station movements to be detected in the laser or VLBI observations, as a practical matter it is best to apply all known changes to the site locations whenever possible.

4.3.4 Modeling Program

4.3.4.1 Chandler Wobble

The causes of excitation and damping of the Chandler motion are among the more important problems of earth motion. Improved knowledge of the amplitude of the wobble will come as a result of several high-precision measurements made with a homogeneously distributed set of stations over periods of at least five to ten Chandler cycles.

If earthquakes or their associated crustal deformation do contribute to the excitation of the wobble, then changes in the pole path (after the annual motion is removed) on a time scale short compared to the period (14 months) of the wobble should exist. The identification of any such changes and their relationship to other phenomena will be of prime interest in the program.

4.3.4.2 Annual Motion

In terms of understanding the Chandler wobble the annual motion is of interest only as a possible exictation mechanism and because it needs to be removed from the polar motion data.

4.3.4.3 Precession and Nutation

Precession and nutation constants can be improved from VLBI observations, but present limitations are probably in the theory, which needs to be redeveloped in light of recent developments in lunar and planetary theory and studies of the effect of the earth's rigidity. This is a major development area, but is presently not thought to be a major difficulty in deriving polar motion.

4.3.4.4 Effects of Mass Shifts on Polar Motion and ..ɔtation Rate

Movements on the earth can change the relative position of the lithosphere with respect to the center of mass of the earth; theoretical models are required for the effect of atmospheric and oceanic phenomena. Observationally, fixed observatories must be established to attempt to detect these motions, since they affect the definition of latitude and hence polar motion and/or precession and nutation. The VLBI and laser ranging observatories discussed in this document should be adequate for this purpose.

4.3.4.5 Interior Structure

For a complete understanding of the dynamics of the earth's interior the variation of density, both laterally and as a function of radius, is of major importance. The analysis of seismic and free oscillation data can provide information on this variation, and should permit the derivation of density contrasts by inversion techniques. The modeling of the interior density may also provide information on the core-mantle boundary, its location and (possibly) shape, and influence concepts of core motions and interactions with the mantle.

4.4 REGIONAL MEASUREMENTS AND MODELS

4.4.1 Introduction

The purpose of making regional-scale measurements is to understand the strain field in tectonic regions, the changes in these strain fields, and their relationship to earthquake occurrence and interplate motion. As we have pointed out in preceding sections, strain is being accumulated and released in areas that are hundreds or thousands of kilometers in horizontal extent, so the program of measurements requires the use of laser ranging or VLBI methods to measure the relative position of a network of points at intervals of a few hundred kilometers. Where possible, this network will include fixed observatories as observing sites.

Because of the limited number of mobile VLBI and laser ranging facilities, mapping the strain field requires filling in the network (densification) using other means. This could conceivably be done with conventional ground surveys, although such an approach hardly seems feasible because of the time and costs involved. A better approach is to use GPS-based highly mobile systems, spaceborne laser ranging, or second-generation "mini-mobile" laser ranging stations (see Section 6.6). Four GPS/VLBI stations of the SERIES type (MacDoran, 1979), for example, could easily densify the North American regional deformation network described below, at intervals of 40-60 km, three times per year. Periodic local surveys within a few tens of kilometers of each recording site will also be needed; these can be done by conventional surveying methods, spaceborne laser ranging, SERIES-type GPS systems, or in the case of the TLRS, by laser ranging to ground targets.

Since relative position and relative movement of recording sites are the important quantities in studies of this type, absolute geocentric position is not required, and regional studies can be carried out in areas where there are no fixed observatories. It is obviously desirable, however, to tie the regional deformation observations to the worldwide network of fixed stations.

The Crustal Dynamics Project Plan, now in its developmental stages, will contain a detailed schedule and plan for deploying the mobile VLBI and laser ranging facilities for regional studies, beginning with the highest priority area, western North America. It must be kept in mind that this whole

schedule will almost certainly be radically revised after the first few years of observing, as a result of discoveries in the initial phases of the research. There are at least three reasons for this expectation. First, logistic difficulties may preclude continued observations at some sites or in some areas, necessitating minor changes in sites and schedule. Second and more important, since we do not know what strain changes will be found, the strategy at present is necessarily based on certain assumptions, and these may well turn out to be invalid. The strategy described in this plan is simply to blanket each region with more or less uniformly distributed networks or profiles, in order to get a first-order look at the deformation. The only situation in which it would be appropriate to continue this method of observation would be if the strain changes are uniformly distributed in space and time, and this seems unlikely. Crustal deformation may well be taking place in rather narrow zones separated by regions of little deformation, but we do not yet know where the active zones may be.

The third reason that the observing schedule will probably be changed is that in order to meet one of the primary objectives of the whole program - understanding the relationship between plate deformation and earthquake occurrence - the mobile VLBI and laser ranging stations must be capable of rapid deployment to the epicentral region of any major earthquakes that may occur in or near the regions under routine study. The Interagency Coordinating Committee for the Application of Space Technology to Geodynamics is now formulating a contingency plan under which the diversion of the mobile VLBI and laser ranging stations to these epicentral regions will be carried out, as part of the interdisciplinary studies of major earthquakes.

It is expected that broad-scale strain changes large enough to be detected with measurement accuracies at the few-centimeter level will be found only in tectonically active regions, and these are all associated with existing or incipient plate boundaries. Therefore our attention is focussed on plate-boundary deformation.

The specific objectives of regional studies in these areas are: (1) to determine the distribution of strain and strain rate in the region; (2) to determine the rate of motion on major faults in the region; and (3) to determine whether fault motion and strain rate are uniform or episodic in time. There are three types of plate boundaries, and the deformation pattern associated with each one is different from the others.

Because of the earthquake hazard to American life and property, our starting point is the western part of North America, where the North American and Pacific plates are moving transcurrently past one another in the San Andreas Fault zone. Horizontal movement is dominant in such a situation, although there are vertical movements near the San Andreas Fault that are not well understood (e.g., the Southern California uplift).

We are after a general understanding of deformation at transcurrent or strike-slip plate boundaries. In order to avoid misinterpretation of data that are affected by local geological peculiarities, it is necessary to make similar observations at other examples of strike-slip boundaries. There are only two such boundaries well exposed on land where the tectonic situation is reasonably simple: the Alpine Fault in New Zealand and the North Anatolian Fault in Turkey. The latter is a logical candidate for study by European scientists (European Space Agency, 1978), so we have included the Alpine Fault in the NASA plan as another example of a strike-slip plate boundary.

The second type of plate boundary is that where plates are colliding, and one plate is being thrust under another. The collision zones can occur on land, as in the Himalayas (where India is moving northward into Asia), and in the oceans, where parts of oceanic plates are being subducted (descending into the mantle) at the collision boundaries. Subduction zones form much of the boundary of the Pacific Plate (Figure 3.2-1). Where continent is present on one side of the subduction zone, as on the west coast of South America and the south coasts of Mexico and Alaska, both vertical and horizontal movement of the land is expected as the over-riding plate is uplifted, foreshortened, and flexed about a horizontal axis. To study the characteristics of collisional boundaries, it is best to avoid the complexities of continent-continent collisions and begin with those that are simpler. South America and Alaska were chosen for study in the NASA program.

The third and last type of plate boundary is where the plates are moving away from one another, as on the world-wide ocean ridge system and in East Africa. In the ocean spreading boundardies, the problem is to find land reasonably close to and on both sides of the spreading axes. Along much of the ocean ridge system the rates of movement are too small to be detected in a reasonable time with equipment having

few-centimeter accuracy. An exception, where neither of these two difficulties is present, is the region of the South Pacific between Fiji and New Caledonia, and this area is included in the NASA plan.

It must be emphasized that the proposed mobile station sites shown in the figures in the following sections are tentative, and that the actual number and location of sites will be chosen with the cooperation and approval of other organizations: in the US through the ICCG Working Group on Site Selection, and in foreign countries through the scientific community and relevant government agencies.

We take up each of the three types of plate boundary observations separately in the following sections.

4.4.1.1 Accuracy Requirements

The plate velocities in areas selected for study in this program are of the order of a few centimeters per year, so the regional-scale deformational velocity measurements must have an accuracy of a few millimeters per year. Such accuracies will permit comparisons of the regional motions with global ones, and will permit regional differences to be detected. Figure 4.2-1 shows that such accuracies should be attainable with few-centimeter accuracy in the baseline determinations within about a decade of the beginning of the measurement program.

For the regional measurements to be useful in a long-term earthquake prediction program, then an upper bound on the accuracy required for the rate determination Δv is given by $\Delta v = v\Delta T/T$, where T is the repetition time between earthquakes, ΔT is the accuracy required in predicting time of occurrence, and v is the relative movement across a fault zone. For T = 100 years, and assuming ΔT to be 5 years and v to be 5 cm/year, this gives Δv = 0.25 cm/year.

Equally important in estimating the rate of motion is the determination of whether the strain rate is steady or episodic over time scales of a decade. If it is episodic, then one consequence is that the repetition period may have little meaning for earthquake prediction. To determine whether there are velocity changes requires regular observation at the accuracy stated above, over a decade or two at least.

A third important question relates to the distribution of the accumulated strain between the points that have been observed to move relative to one another. On the scale of tens of kilometers this is a local problem, but to determine where most of the strain is accumulating, it is necessary to make distributed measurements on a scale of a few tens or hundreds of kilometers, so that local measurements can be confined to a manageable number of small areas within the larger region. This implies that velocity must be determined with sufficient accuracy to identify which parts of the region are deforming or are subject to the largest strain changes. The accuracy of 0.25 cm/year averaged over a decade is adequate for this, but the network must be designed so that the distribution of strain can also be estimated. This is the basis for the program strategy of occupying rather widely spaced points with mobile VLBI or laser ranging stations and filling in between these points with more highly mobile systems (such as the "mini-mobile" laser ranging system or GPS/VLBI systems) or spaceborne laser ranging.

4.4.2 Strike-Slip Plate Boundaries

4.4.2.1 Objectives

The general objectives for study of regional deformation near strike-slip or transcurrent plate boundaries are as given in the preceding section. The main characteristic of these areas is that regional deformation is dominated by horizontal shear across strike-slip fault zones, both sides of which are exposed on land. Regional deformation extends a considerable but unknown distance away from the actual plate boundary, and there may be extensional or strike-slip movement on many other faults away from the major fault system. Vertical movements also occur, and these are important because their relationship to the major deformation is not well understood (see, for example, Walcott, 1978a; Savage and Prescott, 1979).

All or part of the plate boundary may be locked or immobile: the Alpine Fault in New Zealand is apparently locked at present (Walcott, 1978a), as is the San Andreas Fault in Southern California. Continuous non-radiative creep is taking place on the San Andreas Fault in Central California (see Sections 3.2.2 and 4.1.2.1). The strategy discussed in Section 4.4.1 leads to an observing network consisting of sites for mobile VLBI or laser ranging stations in the expected zone of deformation spaced 200-500 km apart, with intervening spaces filled in by the advanced systems discussed in Section 6.6.

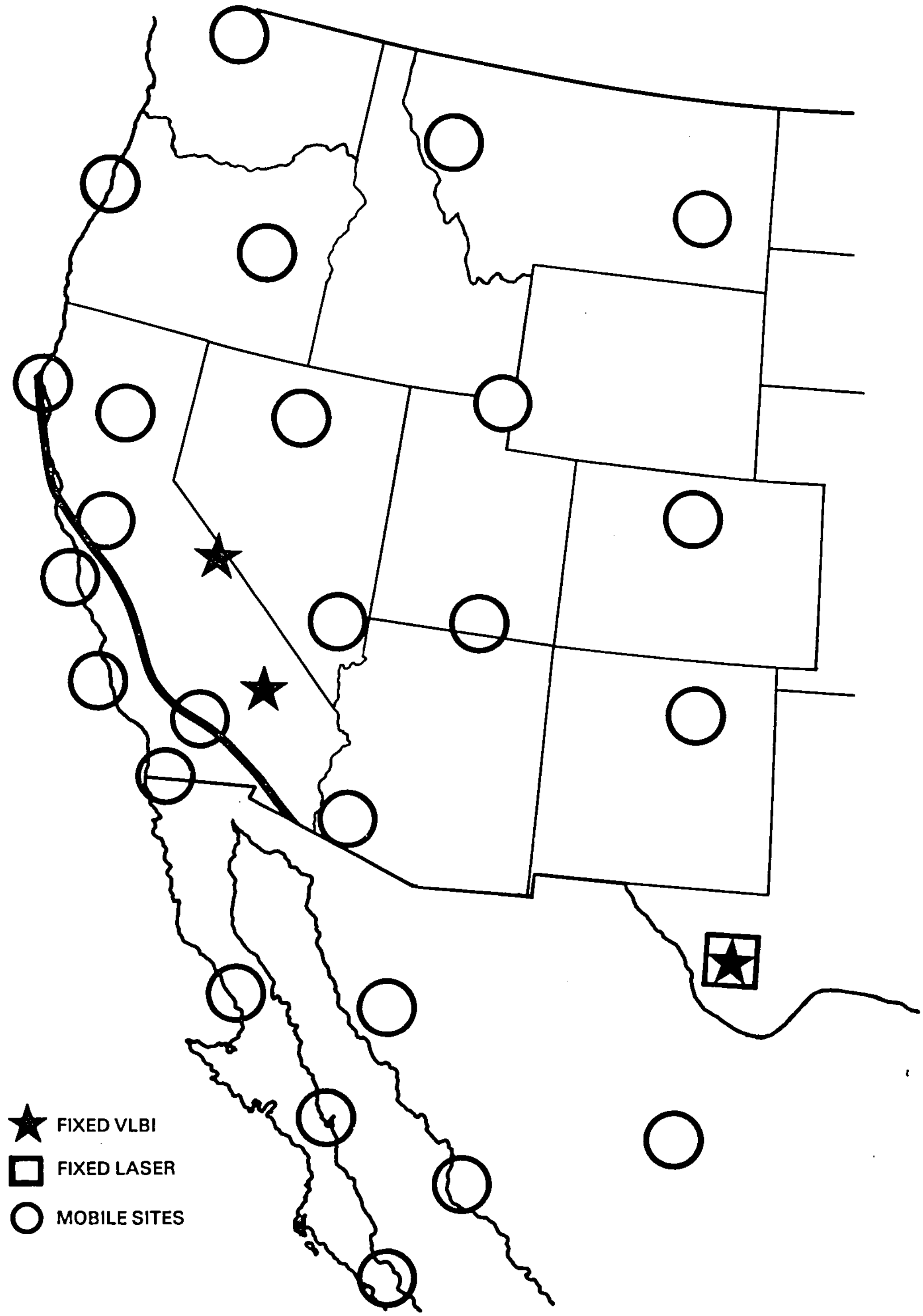


Figure 4.4-1. North American regional strain network.

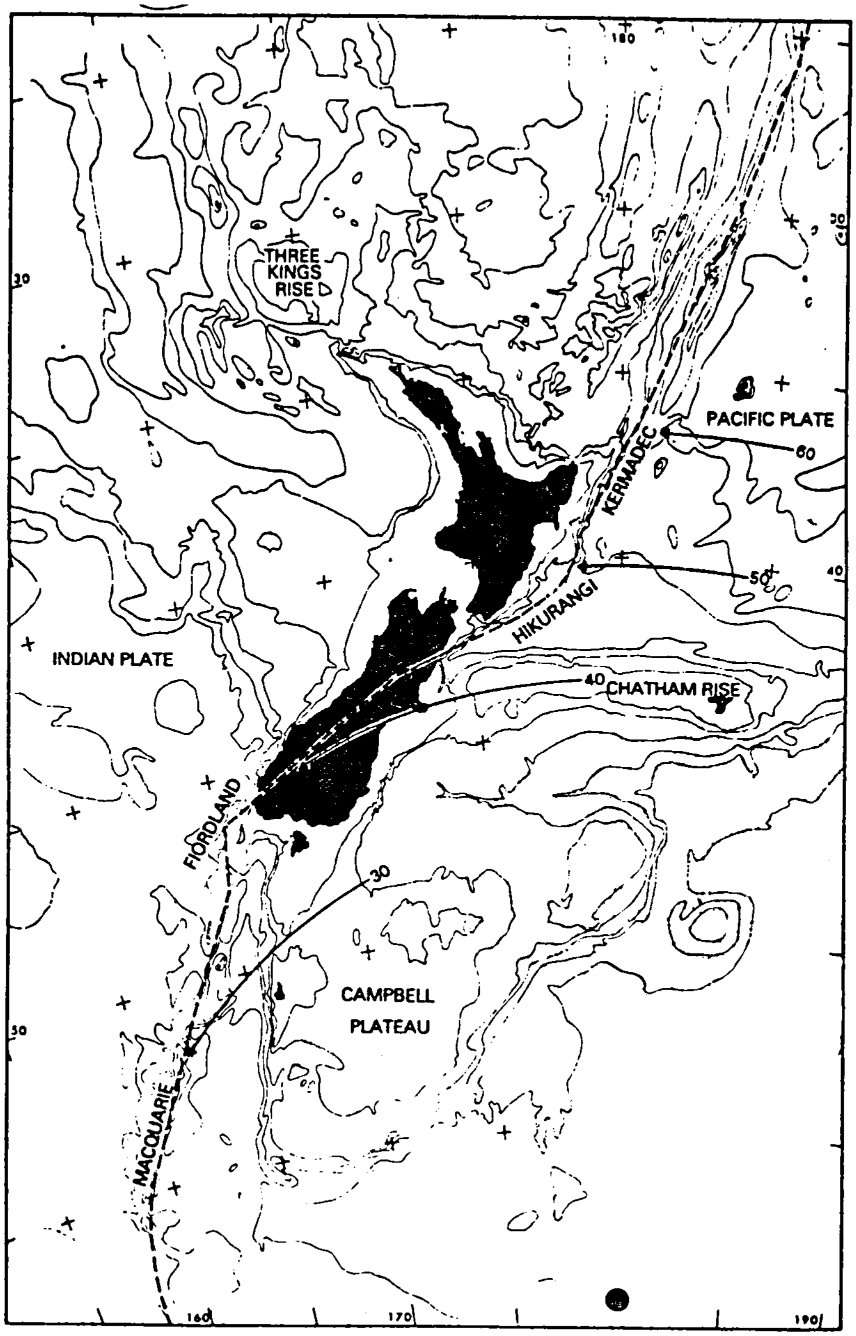


Figure 4.4-2. Generalized tectonics and bathymetry near New Zealand. The Australian-Pacific plate boundary is marked by dashes, and the pole of rotation is shown by the circle at lower right (from Walcott, 1978a).

Strike-slip plate boundaries selected for study in the NASA Crustal Dynamics Program are the western part of North America and the Alpine Fault in New Zealand. Activities in these areas are discussed in the following sections.

4.4.2.2 North American Regional Deformation

The tectonic setting of the western part of North America has been discussed in Section 4.2.2.3, and the faulting motion found there has been discussed in Sections 3.2.2.1 and 4.1.2.1. The general strategy mentioned in Section 4.4.1 leads to an observing network extending from the Pacific coast to the Colorado Plateau (Figure 4.4-1). About 25 mobile sites will be occupied by laser ranging or VLBI stations, and the fixed observatories at Fort Davis, Goldstone, and Owens Valley will be part of the network. The sites are spaced about 500 km apart in the eastern and northern parts of the network, with spacing decreasing to 100 km or less near the San Andreas Fault. The SAFE sites at Quincy and Otay Mountain (California) will be part of the network. It is highly desirable to extend the network northward into British Columbia so that deformation associated with subduction there can be observed.

4.4.2.3 New Zealand Regional Deformation

New Zealand lies on the boundary between the Pacific and Indian-Australian plates (Figure 4.4-2). The two islands that make up New Zealand are on a broad expanse of continental crust that runs southeast-northwest from the Campbell Rise to the Three Kings Rise in the Tasman Sea. The Macquarie Ridge runs northward from a triple junction with the Southeast Indian Rise and the Pacific-Antarctic Ridge into the Fiordland Margin at the southern end of New Zealand. The plate boundary continues along the Alpine and Wairau Faults to the Hikurangi Margin off the east coast of North Island, and into the Tonga-Kermadec Trench to the north (Figure 4.4-3). According to the model of Minster et al. (1974) and Minster and Jordan (1978), present-day plate motion of 4 to 6 centimeters per year is as shown by the arrows in Figure 4.4-2. Subduction is taking place along the Hikurangi Margin in the north and in the Fiordland Margin in the south, with nearly strike-slip motion occurring along the Alpine Fault. Small back-arc rift zones are present in the extreme north and south of the country.

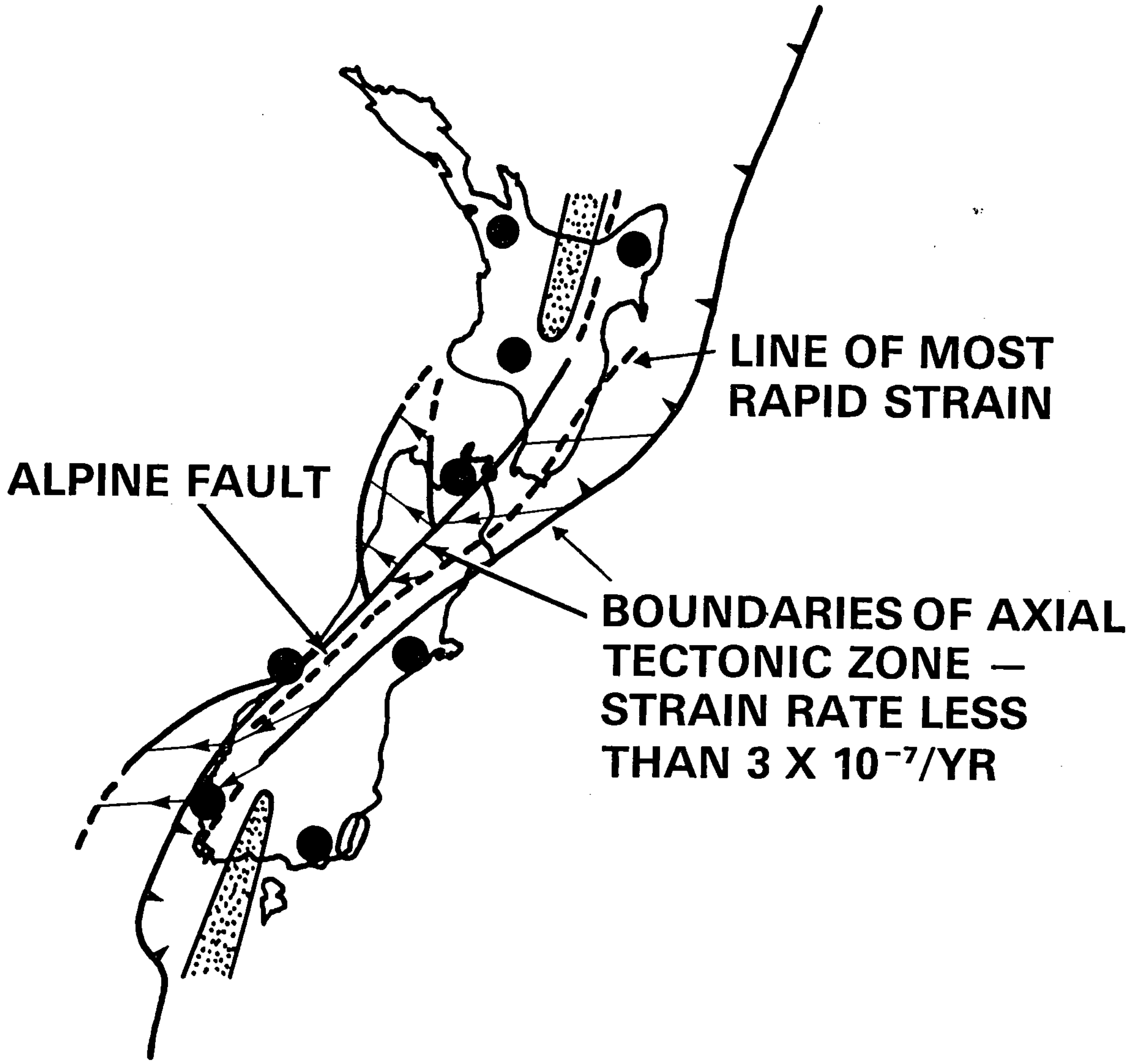


Figure 4.4-3. Tectonic deformation in New Zealand (from Walcott, 1978a), showing proposed locations of mobile station sites.

In a comprehensive study, Walcott (1978a, 1978b) has reported earthquake focal mechanisms and geodetic resurveys carried out between 1870 and 1974. He showed that present tectonic movement is in the general direction and amount predicted by the plate tectonic model. However, the motion appears to be taken up in continuously distributed strain (more than 10^{-7} per year) in the Axial Tectonic Belt rather than in movement on faults. At present there is no movement observed on the Alpine Fault. The strain in the Axial Tectonic Belt is distributed over a zone 70-100 km wide, as shown in Figure 4.4-3 (from Walcott, 1978b).

This situation is of considerable interest for global geodynamics. New Zealand, Turkey, Guatemala, and Western North America are among the few places where a strike-slip plate boundary is well exposed for study on land. The geological setting of New Zealand appears to be less complex than the western part of North America, so it affords an opportunity to study the same type of plate boundary in a different geological context, thus avoiding the possible obscuration of general features by local geological peculiarities. New Zealand is geographically compact, and has an active and well-established program in geodesy and geophysics.

Space techniques can be used to tie together resurveys being carried out by the New Zealand Department of Scientific and Industrial Research. Figure 4.4-3 shows possible locations for eight sites where mobile laser ranging or VLBI stations could be used to make position measurements. These span the Axial Tectonic Belt and the Alpine Fault, with one station on North Island to tie together the geodetic surveys in the northern and southern parts of the country. Outlying stations could be located on Chatham Island to the east of New Zealand (on the Pacific plate) or on Lord Howe Island in the Tasman Sea (on the Australian plate) to measure deformation across a longer distance spanning the Pacific-Australian plate boundary.

The observing program in New Zealand will be coordinated with the program in the Fiji area to the north (see Section 4.4.5.1).

4.4.3 Subduction Boundaries

4.4.3.1 Objectives

The objectives of the regional measurement program near subduction boundaries are similar to those of studies at strike-slip boundaries, and the general outline of the measurement program is the same.

Subduction boundaries are less well suited to crustal deformation measurements than strike-slip boundaries because only one side of the boundary is exposed on land - the surface trace of the fault marking the boundary is typically offshore in a deep trench being filled with sediment. There are many examples of this type of boundary around the Pacific Ocean (Figure 4.2-5). Despite the fact that the boundary fault is inaccessible and below the surface of the earth, preliminary calculations indicate that strain accumulation in active boundaries such as the west coast of South America should result in easily measurable surface deformation. The type of deformation expected is predominantly vertical uplift, accompanied by horizontal compression normal to the boundary.

In the following sections we discuss the proposed measurement program for several good examples of subduction boundaries.

4.4.3.2 Alaska

Alaska is a region of considerable tectonic complexity. The Pacific Plate in this area is being thrust under the North America plate along the Aleutian archipelago at an average rate on the Aleutian Trench of about 5 cm/year. A well-developed Benioff zone extends northward under the Aleutians and the Bering sea, and the many earthquakes in this region have been intensively studied (for example, see Stauder, 1968; Engdahl et al., 1977; Engdahl, 1977). Teleseismic observations of travel time delays from Aleutian earthquakes give a reasonably clear picture of the descending slab beneath this subduction zone (Engdahl et al., 1977).

In 1964 a great earthquake occurred in Prince William Sound (south of Anchorage) that did great damage in Alaska and generated a tsunami which devastated several coastal areas around the Pacific. The mechanism was a shallow, almost horizontal thrust at a depth of about 12 km. Crustal uplift during the earthquake amounted to almost 4 meters, and releveling across the Kenai Peninsula has revealed continuous vertical motion since the earthquake (Brown et al., 1977; see Figure 4.1-2). This post-seismic crustal movement, the presence of an active subduction zone, and the social and economic importance of the region make it desirable to study this regional deformation as part of the NASA Crustal Dynamics Program. Figure 4.4-4 shows that five sites for mobile stations can be located in the area from the south coast of Alaska to the vicinity of the Denali Fault, in order to delineate the vertical movement associated with thrusting at the south coast as well as possible strike-slip movement along the Denali and Castle Mountain Faults. Because of poor weather conditions that prevail in this area, VLBI stations will be used for this purpose.

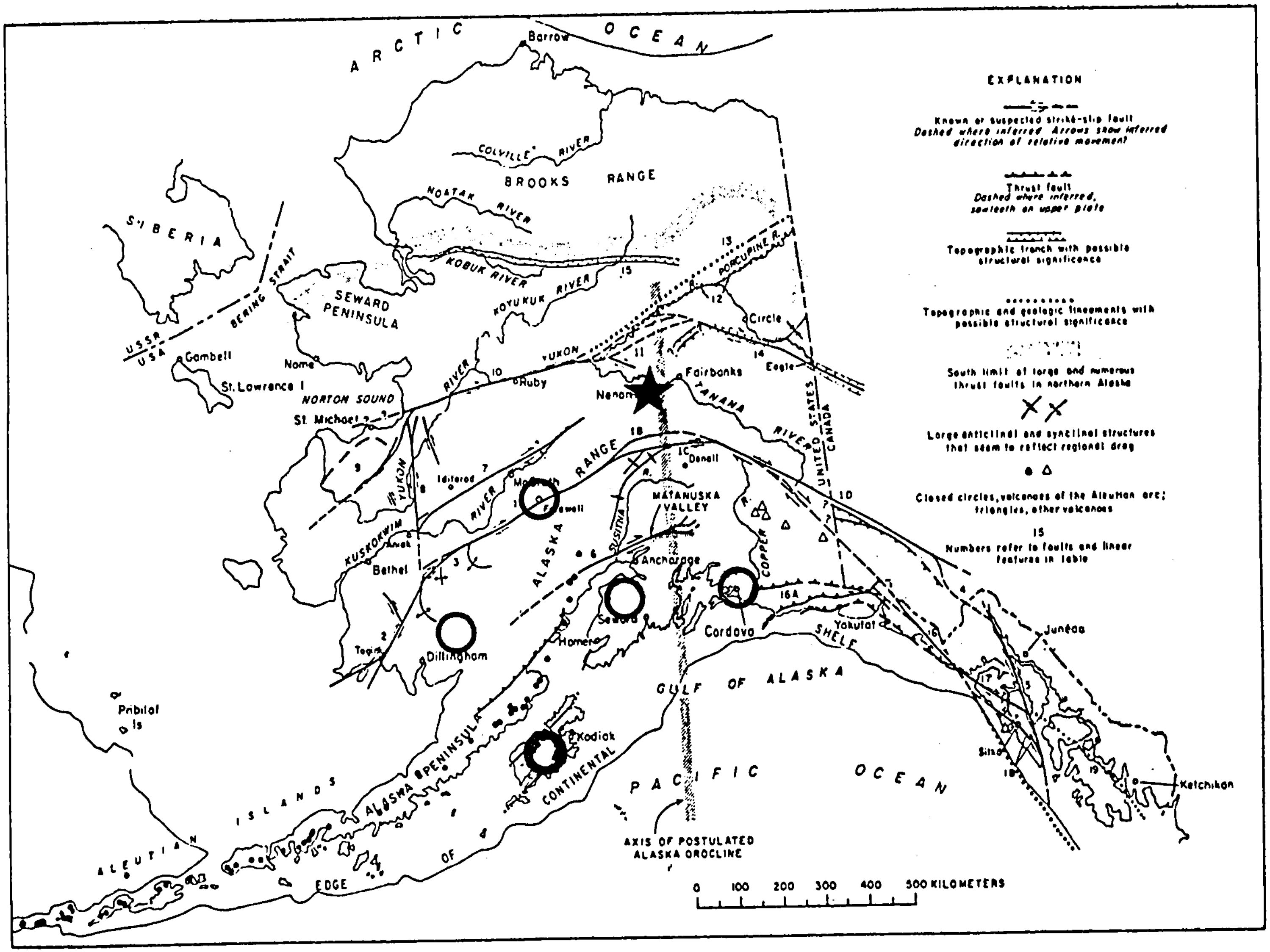


Figure 4.4-4. Tectonic map of Alaska (from Lathram, 1972), showing proposed mobile station sites.

A fixed VLBI antenna in Alaska will be used as a base station for the mobile stations, and for intercontinental observations working with observatories at Goldstone, OVRO, Hawaii, and Onsala (Sweden). This will provide information on the relative movement of the Pacific and North American plates along the Aleutian trench, as well as movement of this part of North America with respect to Europe.

4.4.3.3 South America

Except for its boundary with North America, South America is a reasonably well-defined plate (Figure 4.4-5). The eastern boundary is the Mid-Atlantic Ridge, and the western boundary the subduction zone where the Nazca Plate plunges under the Andes. This subduction zone is the site of many very large earthquakes, presumably resulting from the rapid relative movement of the two plates in this area (nearly 18 cm/year). The Andes mountain system is a good example of an orogenic belt over a subduction zone, a type called thermally driven by Dewey and Bird (1970). In general, the Andes have a crystalline core of Cenozoic batholiths overlain in most areas by Cenozoic volcanics, and a foreland fold belt in which the rocks are overturned and overthrust to the east. There are many active volcanoes in the area. In Colombia the Andes branch into several mountain systems, and there are several postulated microplates or blocks in that area (see also Section 4.4.4.1).

Some features of Andean geology are unexplained. The coast of Peru is underlain not by young turbidites and volcanics, as might be expected, but by two-billion-year-old crystalline rocks. The coast of Chile consists largely of Paleozoic crystalline rocks intruded by Mesozoic batholiths. Thus it seems that the west coast of South America does not represent a simple continental accretion over a subduction zone, as in the basic plate tectonics model. It is clear that the movement of microplates cannot explain the age relationships. Another unresolved problem is the origin of strike-slip faults (such as the Atacama Fault) over the subduction zone.

Despite these complexities, the west coast of South America offers a good opportunity to study an active subduction boundary using the space techniques. Although the actual Nazca - South America boundary is not exposed on

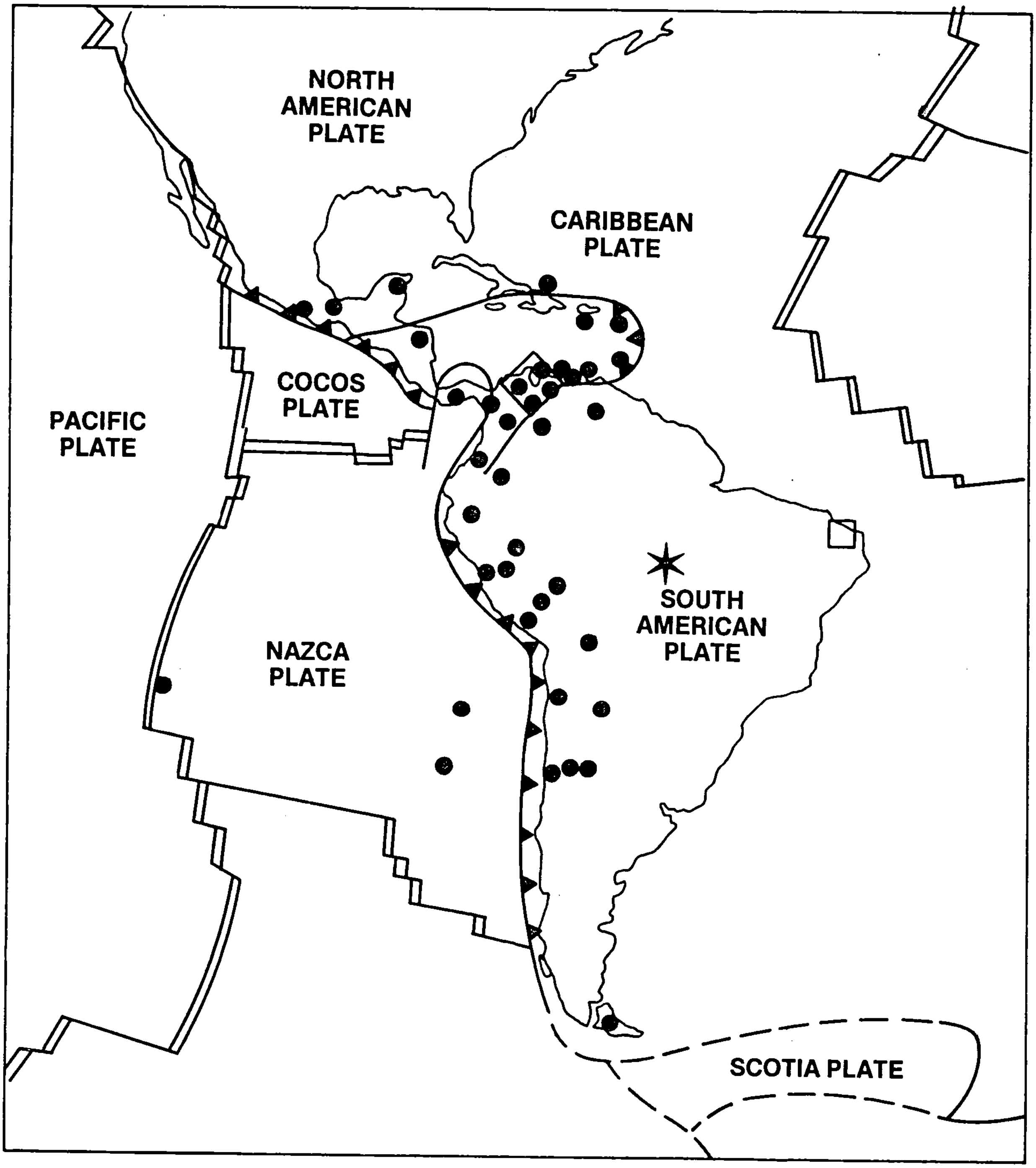


Figure 4.4-5. Generalized tectonics of South America (from Lowman and Frey, 1979), showing proposed mobile station sites.

land, the subducted slab is shallow enough near the coast that strain accumulation at depth should result in easily measurable land deformation (particularly in the vertical component), especially in consideration of the history of large-scale crustal movements in holocene time. For example, Darwin found in 1835 that near Lima the land had risen at least 85 feet since the area was inhabited by humans (pages 369-372 in the 1962 edition of The Voyage of the Beagle). Nothing is known about what the horizontal movement in the north-south direction should be, and observations made over the region from Ecuador to Chile should shed light on the nature of tectonic activity in this area.

For the study of crustal movements in Andean South America, mobile stations can be located at sites arranged in profiles running from the coast over the Andes to the eastern plains. Fourteen such sites are shown in Figure 4.4-5. The VLBI observatory in Brazil would serve as a base station for the mobile VLBI stations. For observation of the relative movement of the Nazca and South American plates, mobile station sites can be occupied on Easter Island, San Ambosio, and San Felix, off the coast of Chile. Finally, a mobile station site can be located in Tierra del Fuego to give information on the location of the boundary between the South American and Scotia plates.

4.4.3.4 Sunda Arc to New Guinea

As a final example of observations across a subduction zone, Figure 4.4-6 shows how VLBI and laser ranging observatories and mobile stations can be used to make observations across the subduction zone separating Australia from Indonesia. There are not many fault-plane solutions for earthquakes in this area, so the rate of movement across the subduction zone is not well constrained, but on the basis of Minster and Jordan's (1978) global model the linear motion across the boundary should be about 7 cm/year. This should be observable with the accuracies characteristic of present and planned VLBI and laser ranging equipment.

By adding one more site in northwestern Australia beyond the Moblas sites already planned (and the fixed observatories near Canberra), the southern side of the boundary can be well covered. Stations can be located on various Indonesian islands on the northern side of the boundary; Figure 4.4-6 shows one possible arrangement of sites. It is clearly

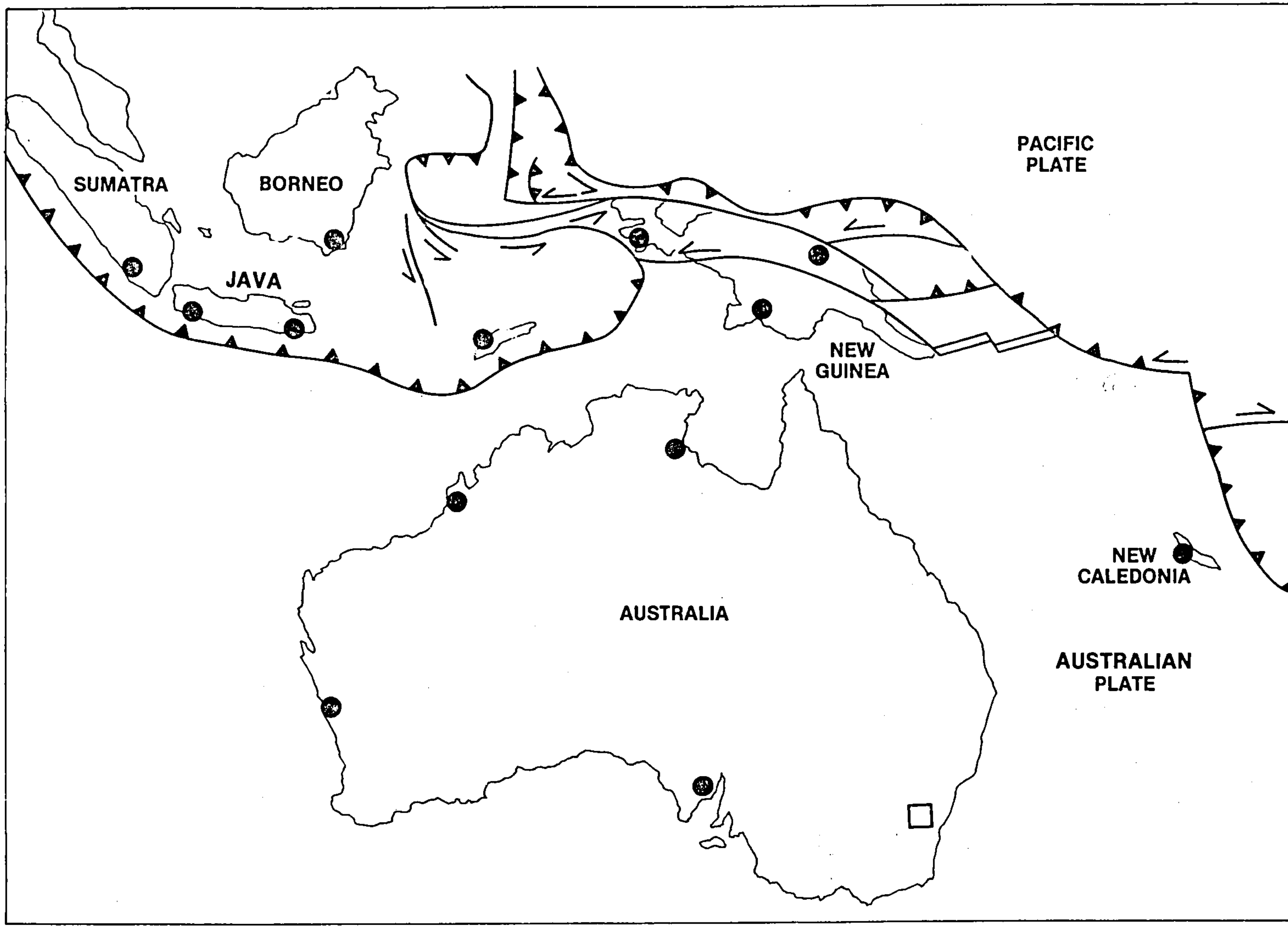


Figure 4.4-6. Generalized tectonics of the Sunda Arc - New Guinea region (from Dewey, 1977), showing proposed mobile station sites.

desirable to extend the observational program into the very complex area of New Guinea and the islands northeast of it, but logistic difficulties and the lack of present knowledge of expected plate motions force this region into a lower priority category.

4.4.4 Mixed Areas

The title simply designates areas where several types of plate boundary are present, and the tectonic activity is too complex to characterize in a simple manner. Two regions of this type, of particular interest and of high priority for the NASA program, are the area around the Caribbean Sea (including northern South America, Central America, and the Antilles) and the area of the Northwest Pacific from Japan to the Philippines. A discussion of possible geodynamics observations in these areas is given in the following two sections.

4.4.4.1 Caribbean Plate and Central America

The Caribbean and Central America are interesting and important areas in the global tectonics model. The origin of this region and its place in reconstructions of past plate movements are still poorly understood (Bowin, 1976). A number of small plates appear to exist here, and their motion has resulted in a zone of intense seismicity and volcanism that stretches over 2000 km from Mexico to Panama. As in South America, the west coast of Mexico is intruded by Mesozoic batholiths. The volcanic belt angles off the subduction zone into the Gulf Coast. Figure 4.4-7 (from Jordan, 1975) shows the general tectonic setting of the area.

Subduction is occurring in the Antilles Arc to the east, and the subduction zone bends around into the mouth of the Orinoco River. The southern boundary of the Caribbean Plate is unknown: it may cross Trinidad and Northeastern Venezuela along the El Pilar Fault, it may be located in or south of the zone of intense shearing in central northern Venezuela, or offshore in the Caribbean itself (Rial, 1978).

Subduction is also taking place along the Middle America Trench off the coast of Mexico and Central America, south of the Rivera Triple Junction at the intersection of the East Pacific Rise. The northern boundary of the Caribbean Plate

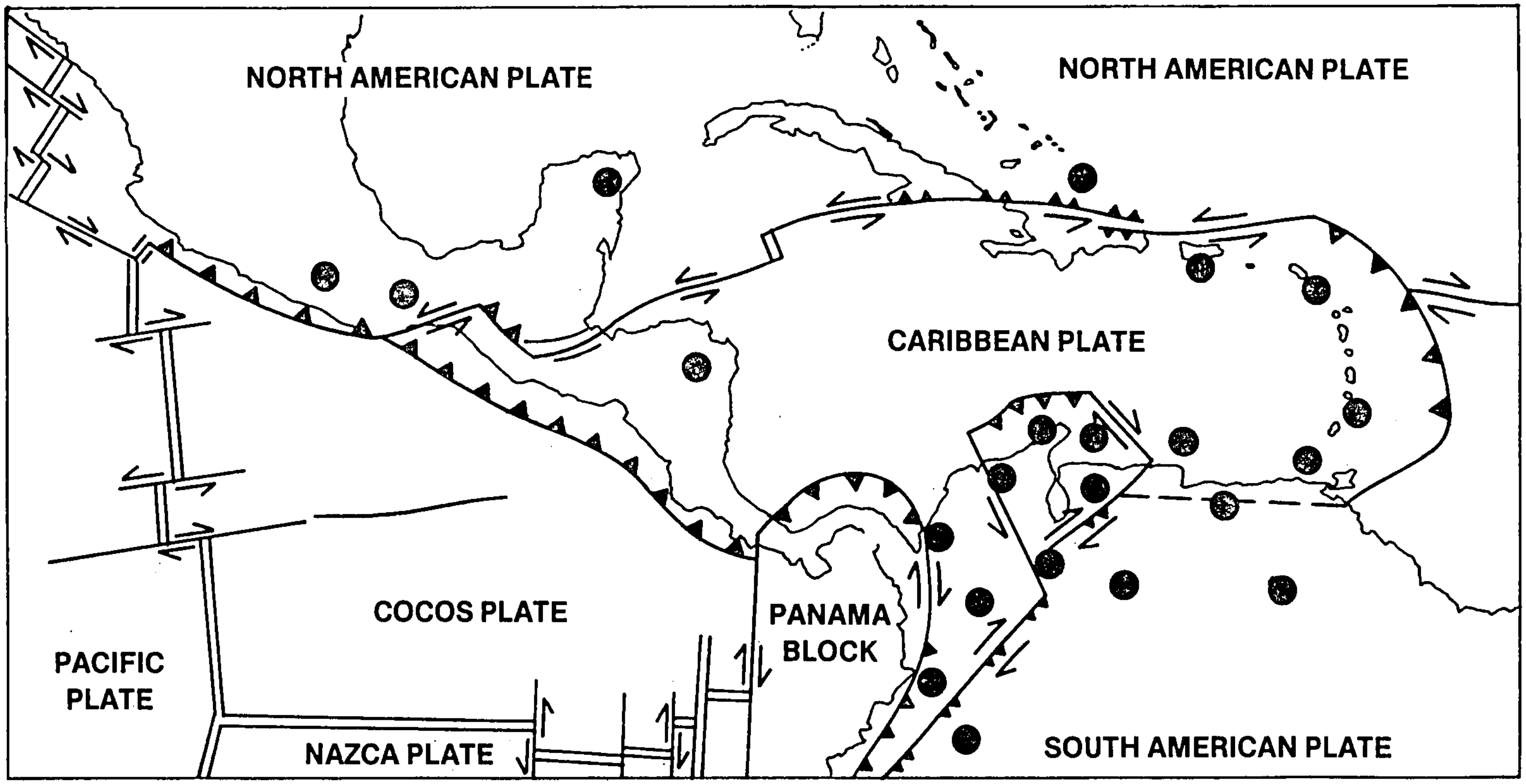


Figure 4.4-7. Tectonic map of the Caribbean region (from Jordan, 1975), showing proposed mobile station sites.

is a left-lateral strike slip boundary, interrupted by a spreading center at the Cayman Rise and possibly by a small subduction zone in Guatemala. Several microplates have been postulated by Jordan (1975) and others (see, for example, Lonsdale and Klitgord, 1978).

A great deal of seismicity occurs in this area, the most recent examples being two major earthquakes in Mexico that filled previously existing seismic gaps (Ohtake et al., 1977; McNally et al., 1979; Singh et al., 1979), and the large earthquake in 1976 on the Motagua Fault in Guatemala.

The region contains examples of all types of plate boundary, as well as the complications that arise when microplates are rotated and ground between larger plates. There are other unusual features: for example, there are indications that the Caribbean Plate is frozen in place, i.e., not moving with respect to the underlying mantle. The subduction zone at the Middle America Trench appears to be either offset or bent at the boundary between the North American and Caribbean Plates.

In the Puerto Rico Trench, deep layers of the oceanic crust are exposed on strike-slip and possibly thrust faults. This area has been the subject of an increasing number of geophysical studies (see, for example, Jordan, 1975).

An interdisciplinary study of this area is being planned by a group of scientists, and a preliminary report made at two workshops in 1978 sponsored by the Lunar and Planetary Institute in Houston calls for a combination of geological studies (using infrared, visible, and microwave remote sensing), marine geophysical observation of magnetic anomalies and crustal structure, studies of crustal deformation, and studies of active volcanoes. The proposed program concentrates on four main problem topics: (1) present plate movements and crustal deformation; (2) past plate movement; (3) delineation of geothermal fields; and (4) studies of volcanic eruptions.

Because of the importance of this region to understanding global geodynamics, and the initiative being taken for a multidisciplinary study including crustal movements, the NASA Crustal Dynamics Program will make position determinations with VLBI and laser ranging stations at selected points in the area. Figure 4.4-7 shows twenty-three sites

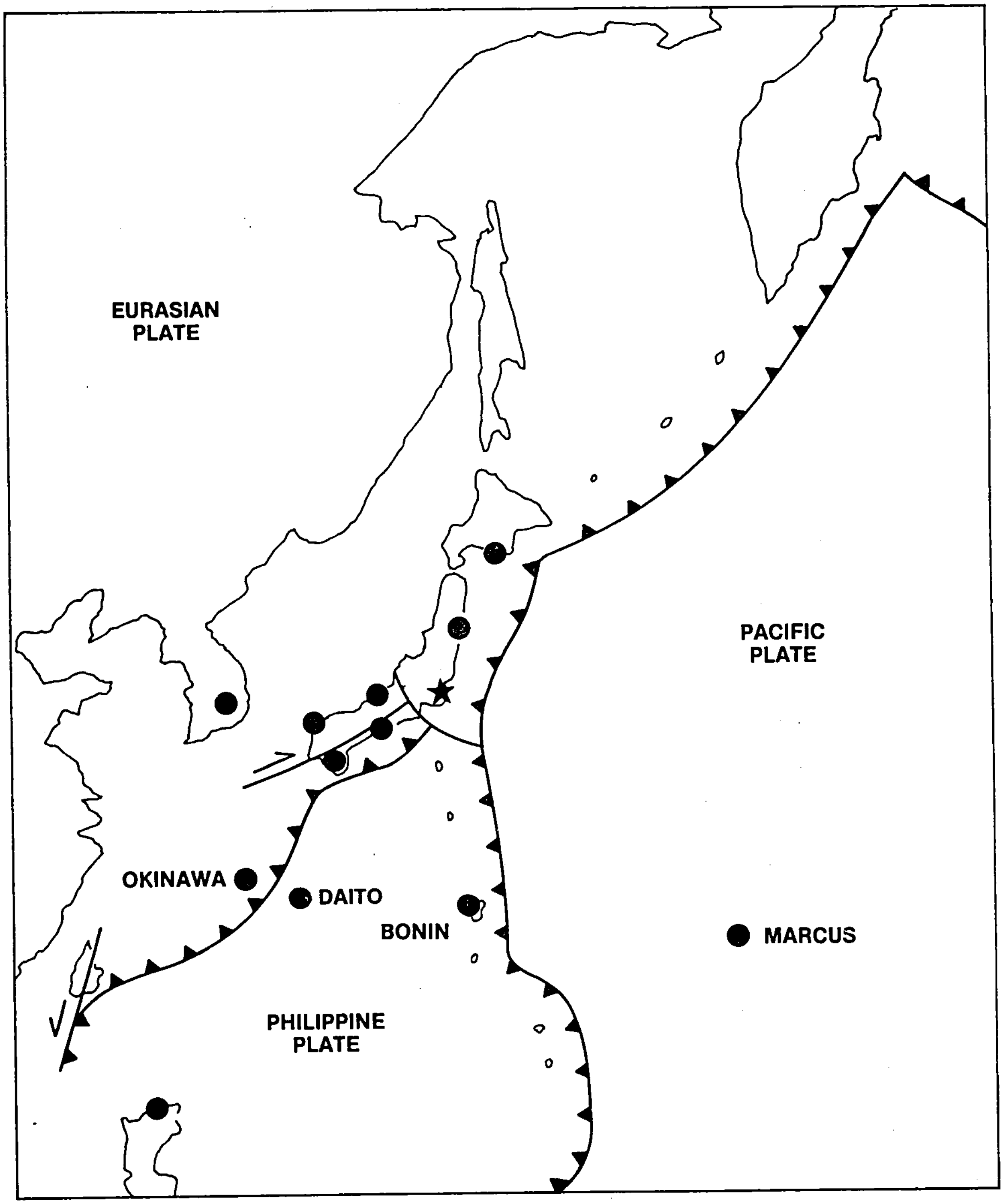


Figure 4.4-8. Generalized tectonics of the area around Japan (from Dewey, 1977), showing proposed mobile station sites.

tentatively selected for this purpose. Sites in Southern Mexico, Honduras, and Panama will directly support the multidisciplinary study proposed by the LPI workshop and seismo-tectonic studies being undertaken by Mexican-US teams (for example, Singh et al., 1979). The other sites are intended to provide information on the deformation of the Caribbean Plate and its motion relative to other plates. The Bahamian site (Grand Turk) is already prepared for occupation by Moblas facilities as part of the Seasat-A tracking network; other sites will be in Puerto Rico, the Antilles, and South America.

The sites in South America are intended (1) to help locate the southern boundary of the Caribbean Plate and define its motion relative to South America; (2) to determine the existence of the Maracaibo, Colombian, and Panama blocks, and their movement relative to the larger plates; and (3) to define the nature of contemporary faulting movements in northeastern Venezuela.

As in South America, observations in this area will be supplemented by ground-based surveying and by geodetic surveys. Mexican sites will be integrated within the framework of the mapping program of the Mexican National Mapping Agency (Detenal).

4.4.4.2 Japan and the Northwest Pacific

Japan lies on the eastern edge of the Eurasian plate at the intersection of two major plate boundaries, and is undergoing intense deformation as the Eurasian plate is being thrust over the Pacific and Philippine plates (Figure 4.4-8, from Dewey, 1977). The Median Tectonic Line and the Fossa Magna are major tectonic features, but most of the shallow earthquakes in Japan are due to crustal rupturing associated with the Nankai Trough and Japan Trench subduction zones. The Japan Trench continues northward as the Kuril Trench, which bends into the Aleutian Trench off the coast of Kamchatka, and continues southward as the Izu-Bonin Arc.

The area offers an opportunity to measure the gross movement of Japan with respect to the Philippine and Pacific plates through location of mobile stations on islands across the subduction boundaries on those plates: Marcus Island, Bonin, and Daito, as well as more distant sites such as

Wake and Luzon. Deformation of the eastern edge of the Eurasian plate can be measured by locating sites in Japan and on the Asian mainland. Finally, crustal deformation within the Japanese islands, which has been measured for many years using conventional geodetic methods, can be observed on a larger scale by the location of mobile VLBI or laser ranging station sites in Japan itself.

Figure 4.4-8 shows how about eight sites in Japan and at least five sites nearby can be used for plate movement and deformation studies of this type. Discussions have begun between US and Japanese scientists on possible joint experiments using space technology. One item of particular interest to both sides is the possibility of joint VLBI experiments using the 26-meter radio antenna operated by the Radio Research Laboratory at Kashima in Central Japan, together with US-operated antennas in North America, Hawaii, and Australia, to measure relative movement of the plates on which these observatories are located. It is anticipated that these experiments could take place in 1983.

4.4.5 Spreading Centers

The third type of plate boundary is that where the plates are moving apart from one another as mantle material is added to create new crust. This is the case at the worldwide ocean ridge system (Figure 4.2-5), and in regions connected to the system. Spreading rates vary, but are usually in the range 2-5 cm/year at the ocean ridges.

It is very desirable to make direct observation of the present rate of movement at spreading centers, but the problem is one of access. On the ocean ridge system there are no places where islands exist, suitable for operation of mobile laser ranging or VLBI stations, on both sides of the ridge and close to it. The East African Rift System is located in a remote part of Africa where field operations would be difficult and expensive. The area around the Fiji Islands appears to offer the best opportunity for measuring crustal movement at this type of boundary.

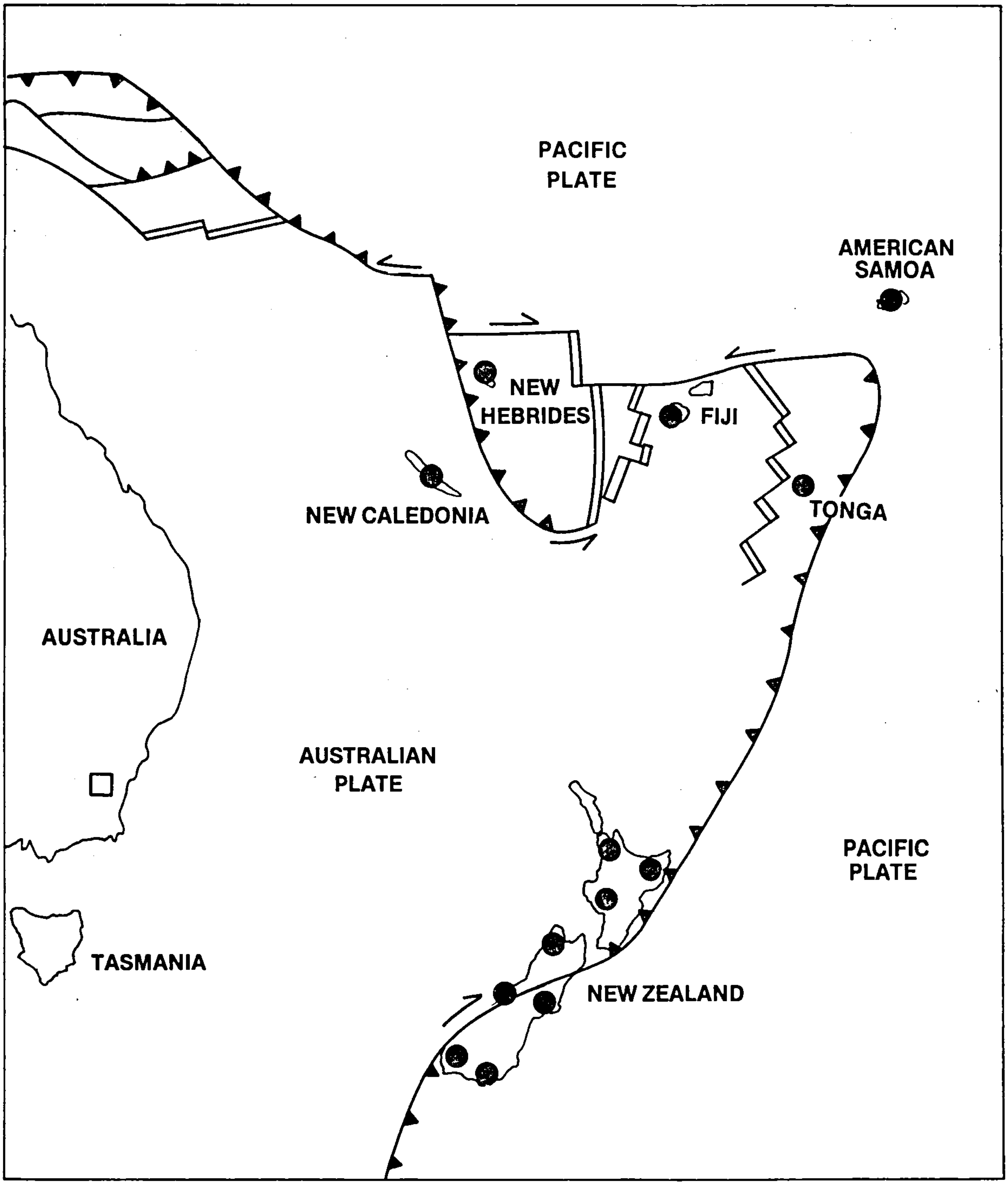


Figure 4.4-9. Generalized tectonic map of the Tasman Sea region (from Dewey, 1977), showing proposed mobile station sites.

4.4.5.1 Fiji Plateau Regional Deformation

In the area between Samoa, New Zealand, and New Guinea, the Pacific and Australian plates are interacting in a complex way with several minor plates (Figure 4.4-9). The Tonga Trench on the east is a subduction boundary between the Pacific and Australian plates; the trench extends into the Hikurangi Margin and Alpine Fault in New Zealand, and the boundary continues south toward the Macquarie Ridge. Another subduction boundary exists under the New Hebrides in the western part of the area, continuing on westward toward New Guinea. Active spreading centers are known to exist in the Lau Basin southeast of Fiji and between Fiji and New Hebrides to the west (Weissel, 1977; Watts et al., 1977; Dewey, 1977; Malahoff, personal communication, 1978). Malahoff estimates the total horizontal crustal movement between New Caledonia and Fiji as 11 cm/year, made up of a combination of spreading at the margin of the Fiji Plateau and subduction in the New Hebrides. This rather large rate of movement should be easily detectable with mobile laser ranging or VLBI stations, and the arrangement of islands in this area makes direct observation quite straightforward. Figure 4.4-9 shows that five mobile sites located in Tonga, American Samoa, New Caledonia, Fiji, and in the New Hebrides can be used for this purpose, complementing stations or sites already planned for New Zealand and Australia. VLBI operations in this area can be done by pairs of mobile stations or by a single station working with the DSN antenna in Canberra, Australia.

4.4.6 Other Regions

There are many other areas of the world where valuable data on plate deformation and plate movement might be obtained, mainly in Africa and Asia. It is intended that studies in at least some of these areas will be taken up in the later phases of the program described here. Two particularly interesting areas are described in the following sections.

4.4.6.1 Middle East Regional Studies

The area from the Eastern Mediterranean to Central Asia contains fascinating examples of all types of tectonic activity. Rifting is taking place in the Red Sea between Africa and Arabia; the Mediterranean is itself a microcosm of tectonic activity; major transcurrent plate boundaries

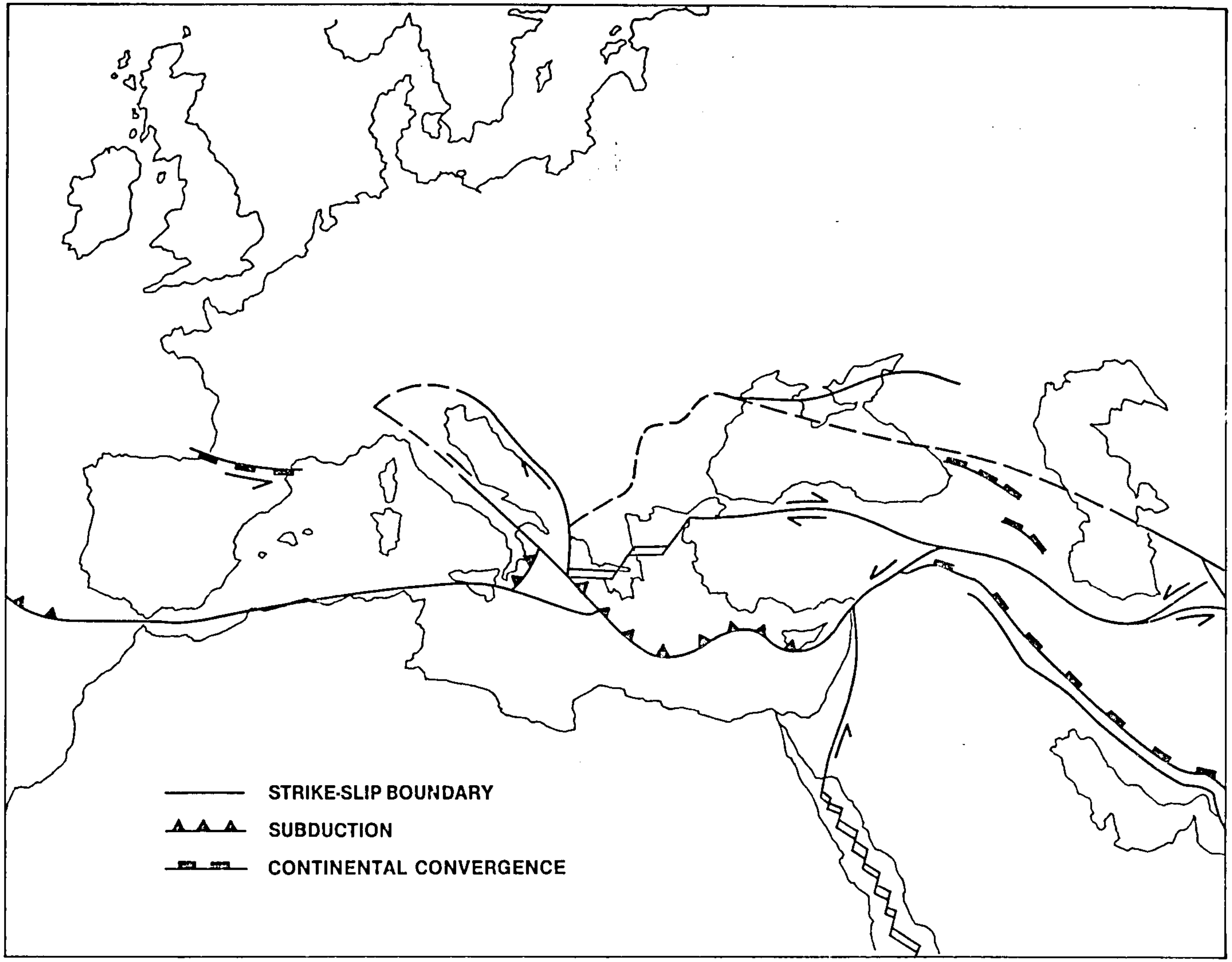


Figure 4.4-10. Generalized tectonic map of Europe and the Middle East (from Dewey, 1977).

occur along the North Anatolian Fault in Turkey and along the Jordan River Valley; complex shearing motion is taking place in Iran, Pakistan, and the Soviet Union. Persistent zones of deep-focus earthquakes in Rumania and in the Hindu Kush indicate the existence of subducted slabs still under considerable stress. Figure 4.4-10 (from Dewey, 1977) is a simplified general tectonic map of the area.

The present state of understanding of this region is rudimentary. Relative plate motion of several centimeters per year are predicted by global models, and these should be detectable using the space-derived systems. Observation of the deformation of plates and microplates as measured by such systems will be important in understanding the general tectonic picture of the area.

Detailed planning for field operations in this region will be undertaken in cooperation with the European Space Agency, and field observations should begin in 1984.

4.4.6.2 Central and Eastern Asia Regional Studies

All types of tectonic activity can be found from Central Asia eastward to the Pacific and southeastward to Indonesia and the Philippines. Some of the most destructive earthquakes in history have occurred in China, Indonesia, and the Philippines; volcanoes occur in many places; a spectacular continent-continent collision is taking place where India is indenting the Asian continent. It is obviously desirable to make observations of regional deformation in these areas, for two reasons: first, to understand better the local tectonic activity; and second, to gain a better understanding of global tectonics and earthquake occurrence through studies of regions where a great deal of activity is taking place.

During the initial phases of the crustal dynamics program it is planned to study the logistics of such operations in these areas, and at the proper time, to discuss possible cooperative programs with the governments of the countries involved.

4.4.7 Gravity Measurements

In order to fully interpret the deformations that are observed it is desirable to combine the geodetic measurements with gravity measurements at the observation sites and

intermediate positions. At some of the primary locations cryogenic gravimeters with long-term stability are necessary, but at the majority of the sites frequent visits by LaCoste-Romberg model D or G gravimeters would be adequate. These measurements will provide information about the change of mass in the vicinity of the point as well as about possible vertical motions (see also Section 4.2.3.1).

Modern gravimeters have a height sensitivity of about 3 mm at best, and about 1 cm in practice, although care has to be taken to correct for surficial geological effects such as changes in water levels, ground temperatures and tidal loading.

On a larger scale it may be possible to interpret gravimetric models derived from space data in terms of the regional stresses that exist in the upper mantle and lithosphere. If this works, the resulting stress patterns could be used to better interpret and understand the observed regional motions, because they reflect the forces that are causing present-day tectonic phenomena. Continued improvement in both accuracy and resolution of global gravity models on a regional scale (100 to 1000 km) is therefore necessary. The present models have resolutions of about 1000 km and accuracies of a few milligal; the required accuracy is approximately 1 mgal with a resolution of about 200 km. This resolution and accuracy is not obtainable from present tracking data and will need to be obtained by a dedicated gravity field space flight mission.

4.5 MEASUREMENTS AND MODELS - LOCAL SCALE

In this section we discuss the contributions space techniques can make to a measurement program on scales of 20 to 100 km. It is over these scale lengths that phenomena can be measured that are most likely to contribute directly to an actual prediction of the time, place, and magnitude of an earthquake.

The objectives of the crustal dynamics program at this scale are:

1. To monitor local crustal deformation and strain rate in seismically active regions.

2. To monitor local land movement in the years immediately following a major earthquake.

3. If a major earthquake is predicted, to monitor land movement near the predicted epicenter before the earthquake occurs.

4.5.1 Approach

The regional measurements described in previous sections provide a broad picture of deformation in seismic regions, and indicate areas where more concentrated study is needed within those regions. A more thorough understanding of these phenomena can be obtained from more frequent and more densely spaced measurements than those contemplated for a program using a modest number of mobile laser ranging and VLBI stations.

There are two attractive alternatives to making more frequent and more densely spaced measurements with the laser ranging or VLBI stations now available. These are: (1) use of GPS satellites as radio sources for VLBI observations; (2) use of a single laser transmitter/receiver on a spaceborne platform to range to passive retroflectors located on the ground.

Global Positioning System

When the Global Positioning System (GPS) becomes operational, the possibility will exist of using the GPS satellites as radio sources for the standard VLBI technique and in other ways that may be equally useful for local-scale

geodesy (Counselman and Shapiro, 1978; Anderle, 1978; MacDoran et al., 1978; MacDoran, 1979). The strong signal from the GPS satellites would enable very small antennas and short site visit times to be used. Such signals can also, of course, be received by the 4m or 9m mobile VLBI facilities. Preliminary studies indicate that very small and highly mobile VLBI receivers can be built for a small fraction of the cost of the quasar-based VLBI mobile stations, and should be able to make a position determination in about two hours. Such systems are affected by water vapor in the atmosphere in the same way all VLBI systems are, so the resulting error of about 3 cm will have to be eliminated by including a water vapor radiometer with the receiver systems. See Section 6.6.1 for further discussion.

Spaceborne Laser Ranging

There are operational advantages in having the laser, rather than the reflectors, in space. The ground reflectors are small and passive, and therefore much less expensive than active laser ranging or VLBI stations. They are easily transported and placed almost anywhere. As the number of resurveys required in the program discussed here increases, the spaceborne laser technique at some point becomes the most cost-effective way of carrying out the regional measurements (Cohen and Cook, 1978; Smith, 1978; Smith and Tapley, 1979). A description of the spaceborne system and the development studies underway is given in Section 6.6-2.

4.5.2 Aftershock Studies

An estimate of the ground motions that should occur prior to an earthquake can be obtained by studying the relaxation of the ground after a major earthquake. It appears that deformations created during and prior to the earthquake often subside in the months and years following a large earthquake; studying these post-seismic motions is perhaps the only way to determine the extent of the deformation. This period is often characterized by a series of aftershocks with magnitude frequently approaching that of the main shock.

Because of the speed with which the relaxation occurs, it is necessary for the measurements to begin immediately after the earthquake, preferably within 24 hours, and to be made at several sites simultaneously. Approximately 15 to 20 sites within a radius of about 100 km of the epicenter

would be monitored at spacings of 10 to 50 km with the more closely spaced locations nearer to the center. These measurements would, of course, complement the ground surveys over more localized regions undertaken by other agencies following an earthquake. The spaceborne laser ranging or GPS/VLBI systems would also find application here.

It must be anticipated that for the next several years it will probably not be possible to predict precisely the location of a very large earthquake. Also, it is not likely that a large earthquake will occur in a region fully instrumented for post-seismic monitoring. Thus highly mobile systems capable of setting up quickly, taking observations and moving to the next site, are required for these post-seismic measurements.

4.5.3 Frequency of Measurements

The monitoring of local regions needs to be more frequent than the regional measurements because the magnitude and variations in strain are larger near active faults than in less active areas. In an operational system the frequency of measurement should be at least four times per year in order to detect sudden, rapid, but possibly short-lived motions. For post-seismic motions, measurements should be made daily or weekly at first, and at least once per month for several years. For this type of operation it would be necessary to reschedule some of the regional measurements in order to divert several systems (VLBI or laser) into the earthquake area.

4.5.4 In-Situ Data Collection

It is unlikely that geodetic measurements alone can be used to make reliable predictions of earthquakes. The ultimate system for earthquake prediction will probably require a dense network of instruments in areas of high seismic risk, continuously monitoring such parameters as seismic activity, ground tilt, and accumulated strain. At present, data from seismometers and other monitoring instruments are returned for analysis by telephone lines or radio relays. In addition to being frequently noisy and unreliable, telephone lines and radio relays are generally inoperative during earthquakes, although in the United States these are probably the most cost-effective method of data transmission. In remote regions, telephone lines are difficult and costly to install and maintain, while radio relays have terrain and

range limitations. Satellite relaying is probably the only effective method of developing a data collection system capable of large-scale crustal hazard monitoring and predicting.

A review of current and potential methods available for satellite relaying of geophysical data has been given by Allenby et al. (1977). Data collection platforms are currently available "off-the-shelf" to relay data from low-bit-rate instruments such as tiltmeters, tide gauges (to determine local elevation), gravimeters and magnetometers. Since seismic data is likely to play an essential role in any ultimate prediction program, however, systems for transmitting seismic data to a central processing station via satellite would be extremely useful.

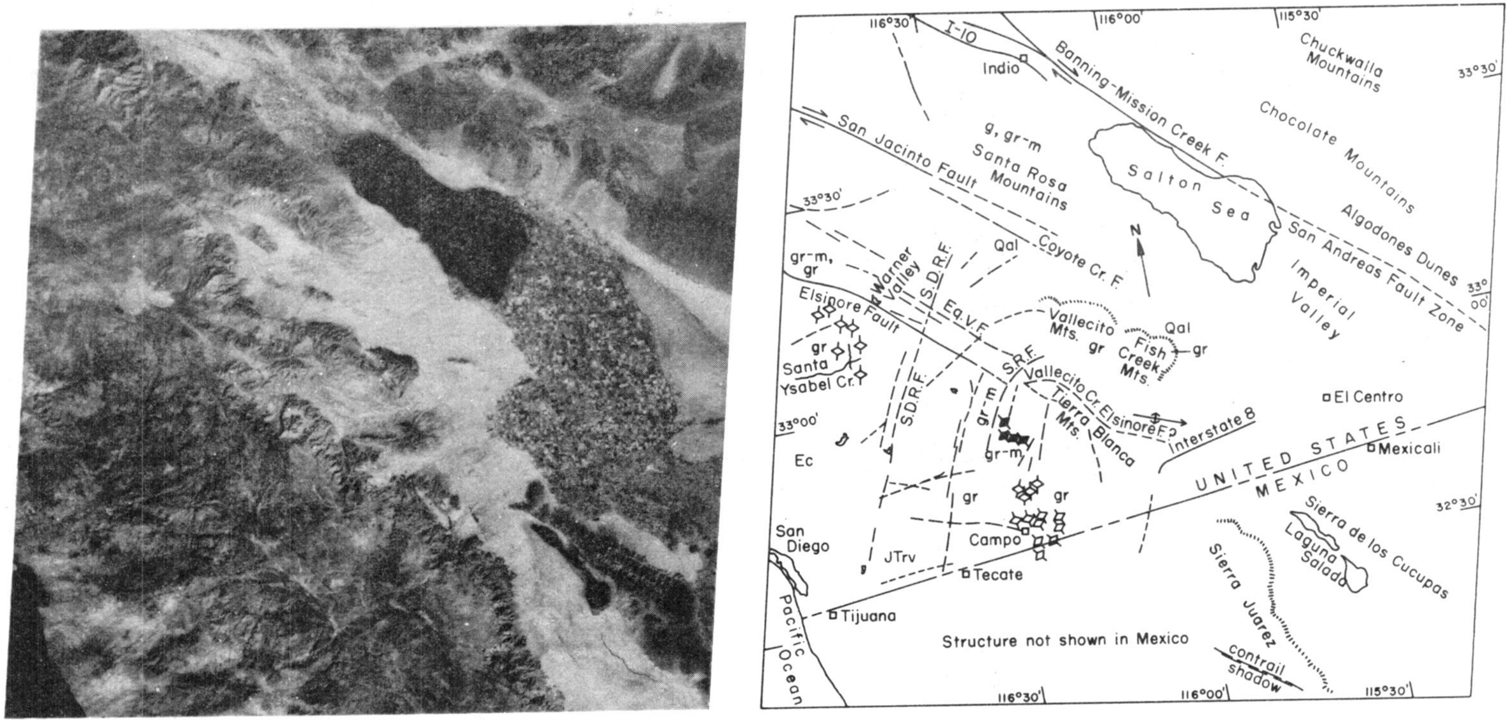
SECTION 5

REMOTE SENSING FOR EARTHQUAKE HAZARD ASSESSMENT/REDUCTION AND FOR RESEARCH IN GEODYNAMICS

5.1 OBJECTIVES

In this section we discuss the application of orbital remote sensing to the general problem of earthquake hazard assessment and reduction, and to the study of large-scale tectonic features related to geodynamic processes.

Reliable earthquake prediction methods will greatly reduce life and property losses from earthquakes. However, in the immediate future no practical technique appears capable of preventing earthquakes or controlling them by reducing their energy release. For this reason, a crucial element of any comprehensive earthquake program is the development and implementation of methods for mitigating the destruction of inevitable future earthquakes. Such techniques include identifying and assessing the hazards of earthquake-prone areas, designing man-made structures to withstand the expected hazards of the area, developing and enforcing building codes that will enable buildings to withstand maximum expected forces, estimating future earthquake or tsunami damage, and planning for adequate post-disaster relief. An important part of the total program is educating the public as well as local and state governments to the dangers involved and possible means of reducing these dangers.



STRUCTURE SKETCH MAP

Peninsular Ranges, San Diego County, California

ERTS-I Image 1106-17504 (6 Nov. 72)

STRUCTURE

Fault (solid where confirmed, dashed where inferred or nature not certain).

Foliation in metamorphic rocks.

Flow structure in intrusive igneous rocks (inclusions, crystals, etc.).

Plunging anticline.

LITHOLOGY*

Qal Quaternary alluvium.

Ec Eocene nonmarine sediments.

gr Mesozoic granite rocks.

gr-m Pre-Cenozoic granite and metamorphic rocks.

*Lithology from Geologic Map of California (1:250,000 sheets)

Paul D. Lowman, Jr.

Figure 5.2-1. Left: Landsat image of Southern California. Right: derived geological structure map.

5.2 REMOTE SENSING OF EARTHQUAKE HAZARDS

A major objective of any broad program of earthquake hazard assessment is the delineation of areas subject to potential damage and casualties associated directly or indirectly with earthquakes. Examples of indirect effects include seismically induced landslides, and flooding resulting from seismic damage to dams. Direct effects are those resulting from ground shaking or surface rupture along fault traces. Orbital remote sensing can contribute to assessment of these hazards in several ways. These are described in the following sections.

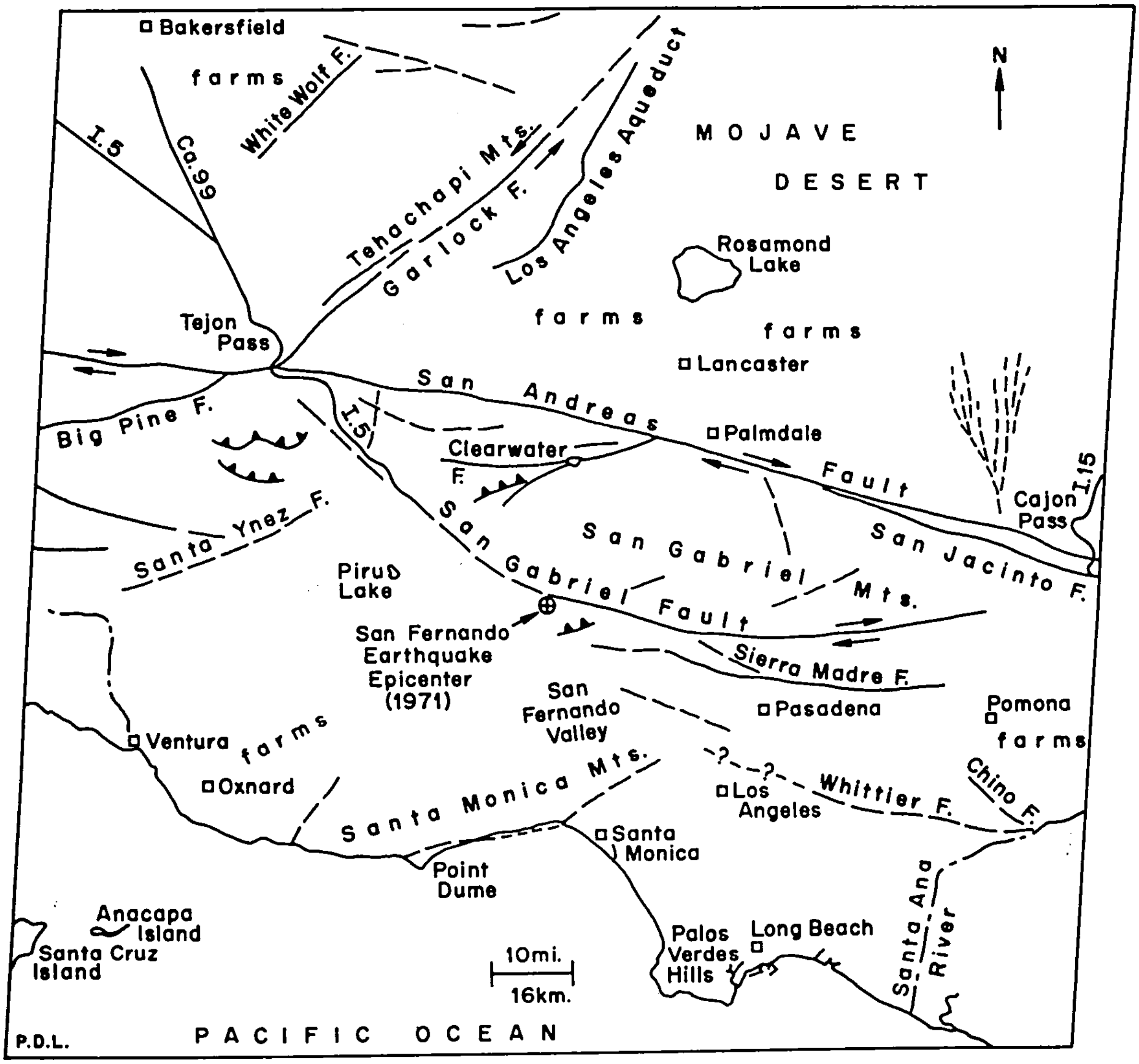
5.2.1 Fault Mapping

When orbital photography became available in the early 1960's, it was found that geological structures in many parts of the world had not been adequately or accurately mapped. This was even true for areas such as California, and even the first Landsat image of California revealed previously unknown lineaments, some of which may be previously unrecognized faults.

According to the California Division of Mines and Geology (1974), knowledge of faults in California is "frequently inadequate for the purpose of evaluating the potential for surface fault rupturing." Furthermore, as C. R. Allen has pointed out, it is difficult to assess the danger from many major faults on the basis of their recorded seismicity, simply because the historical and instrumental records are far too short, even in countries such as China where written records for several thousand years are available.

An example of how orbital imagery can be used to map previously unknown faults in supposedly well-mapped areas is shown in Figures 5.2-1 and 5.2-2. It is clear that this is a useful application of orbital remote sensing to earthquake hazard assessment (Lowman, 1974). However, current earth resources satellites of the Landsat series are not ideal for fault mapping, for several reasons. In addition to limitations imposed by the resolution limits (about 80 meters for the early Landsats and about 40 meters for Landsat-3) the Landsat images for any given area show the terrain with only a narrow range of sun azimuths, thus overemphasizing linear features perpendicular to the sun's illumination and perhaps missing features parallel to it. Furthermore, for low and mid-latitudes, sun angles are too high for optimum fault delineation.

Figure 5.2-2a. Landsat image of the Transverse Ranges (California).



GEOLOGIC SKETCH MAP
TRANSVERSE RANGES, CALIFORNIA
FROM LANDSAT-1 IMAGE 1090-18012

LEGEND:

FAULT (STRIKE-SLIP IF SHOWN WITH ARROWS)

THRUST FAULT (BARBS ON UPPER PLATE)

Figure 5.2-2b. Geological sketch map of Transverse Ranges (from Lowman, 1975).

Several new types of orbital sensing appear promising for fault mapping. High resolution returned-film photographs such as those taken by the Skylab Earth Terrain Camera (Figure 5.2-3), when available for larger areas, will obviously be valuable. Moderate-resolution imagery of the Landsat type, but with low sun angle and variable sun azimuths, will also be of value, especially for areas of low topographic relief. Orbital radar imagery with low depression angles, planned for Shuttle missions, should be investigated for application to fault mapping, since airborne radar has been demonstrated to be useful for this purpose (Figure 5.2-4). Thermal infrared imagery from orbit may also be useful, since Sabins (1978) demonstrated that airborne surveys in the 8-14 micrometer band may reveal many structures (including faults) totally invisible to standard aerial photography. Finally, the Heat Capacity Mapping Mission, launched in May 1978, has as one of its objectives the delineation of geological rock types with a resolution of about 700 meters.

5.2.2 Mapping of Terrain Conditions

Other factors being equal, seismic damage from ground shaking is much worse in areas of soft ground than on bedrock. If the soft ground is water-soaked, the effect is enhanced, and may be accompanied by land subsidence and collapse of buildings. Consequently, remote sensing of ground conditions appears to be of potential value in earthquake risk assessment. Thermal infrared imagery from orbit, supplemented by low-altitude surveys and ground measurements, appears to be of greatest interest. Passive microwave imagery, well known for its use in mapping soil moisture, should be investigated for seismic risk assessment, although the low resolution of such imagery from orbital altitude appears to limit its use. Imaging radar may be of value in mapping terrain conditions to the extent that it delineates the dielectric properties of the target material. Standard Landsat imagery will presumably be of use in planning aerial or ground surveys.

Landslides are frequently the most dangerous secondary hazard associated with earthquakes, particularly in very mountainous regions such as South America. Mapping of landslide areas in seismically active regions is therefore an accepted method of hazard assessment. Because of the high resolution required, conventional air photos will probably continue to be the chief remote sensing method for delineating landslide areas. However, orbital photography should be useful in at least guiding and correlating aerial surveys. Stereosat imagery in particular may be of direct value in supplementing topographic maps in areas such as

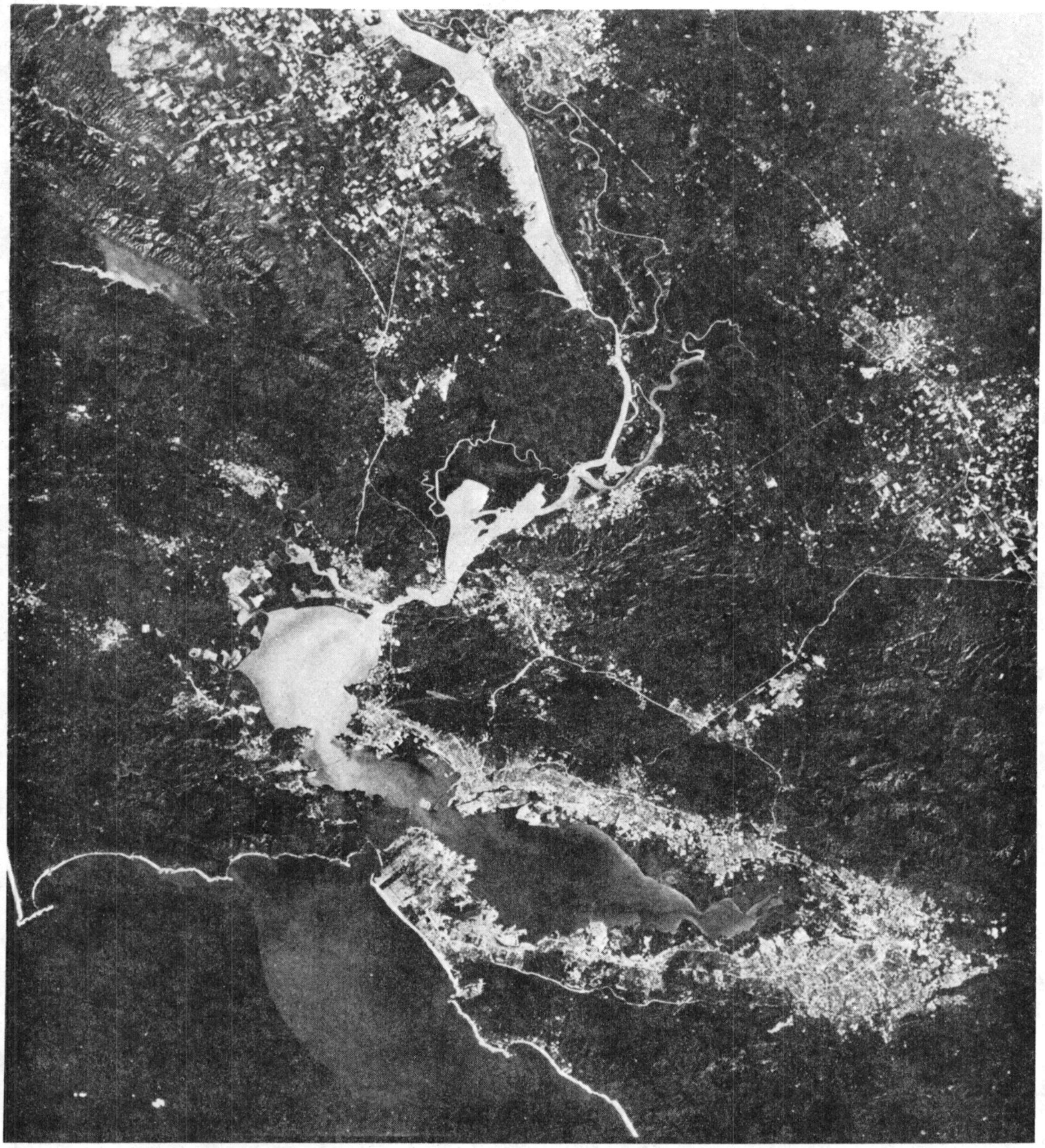


Figure 5.2-3. Skylab camera picture of San Francisco Bay and adjacent parts of the Great Valley (north is to the upper left).

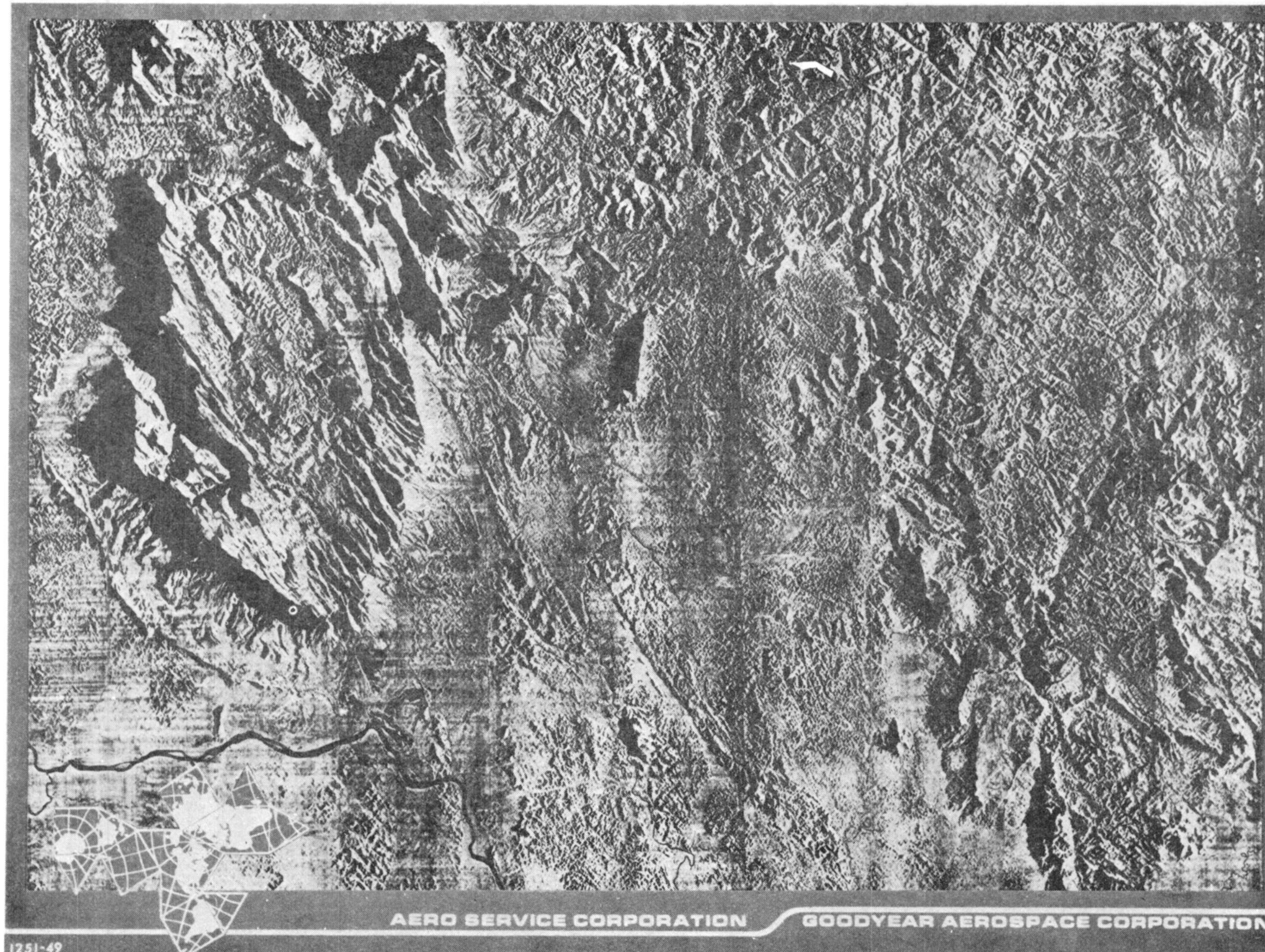


Figure 5.2-4. Side-looking radar image of northern Venezuela from 40,000 feet. Flight lines run north and south. The area is forest-covered.

Alaska and South America. The probable value of color IR imagery in mapping old landslides suggests (Sabins, 1978) that existing and future Landsat imagery will be of value for this purpose; an important goal, since landslides generally occur repeatedly at the same locations.

5.2.3 Tsunami Flooding

Tsunami are a danger anywhere around the Pacific Basin, and a warning system has been in operation for some years. However, planning of future coastal development in this area could benefit from orbital remote sensing in that areas of potential tsunami inundation could be better mapped, e.g., areas of shallow restricted water. With high-resolution imagery, lines of previous inundation could be mapped. A related hazard that could be assessed with the aid of orbital imagery would be the waves produced by earthquake-induced rock or ice falls in fjords.

5.2.4 Flooding from Dam Failures

As shown in Figure 5.2-3, orbital imagery can provide a unique view of all the major surface features, artificial and natural, above a certain size in a large area. In this Skylab picture of the San Francisco area, one can easily identify reservoirs, rivers, urban areas, bridges, and the like. Such pictures may be of value in predicting damage resulting from flooding caused by dam failure during earthquakes. In addition, since it shows the region as a whole, it should be of value to organizations attempting to predict the effect of a major earthquake on transportation routes and other facilities.

If quick-response orbital imagery becomes available it should be useful in post-earthquake damage assessment, thus providing disaster relief agencies with information on where to allocate materials and personnel in recovery efforts. Such surveys are now carried out by aircraft, but a major earthquake affecting tens of thousands of square miles would clearly dictate the use of orbital remote sensing for rapid assessment of the effects of the event.

5.2.5 National Earthquake Risk Evaluation

Production of earthquake risk maps for the entire nation, as well as for specific regions, has been recognized as an important objective of the Earthquake Hazards Reduction Program (OSTP, 1976). The purpose of these maps is to estimate and thus limit damage and loss in advance of a

disastrous earthquake. Orbital remote sensing could be applied to this objective as a logical extension of the efforts described in the previous section, by application to the planning and location of dams, pipelines, nuclear power stations, hospitals, housing developments, roads, bridges, and similar facilities, in order to minimize damage from earthquakes and associated phenomena. Educating the public to the dangers from earthquakes is a continuing problem; orbital photographs could be effective in this regard by providing an objective, easily understood representation of the areas of high risk.

5.3 BASIC RESEARCH IN TECTONICS AND GEODYNAMICS

Orbital remote sensing is beginning to make major contributions to geological research, benefiting from the global coverage, rapid repetition, and synoptic view provided by orbiting satellites. Almost our entire knowledge of the geology of the other terrestrial bodies - Mercury, Mars, the Moon, and the Galilean satellites of Jupiter - comes from orbital remote sensing in previous NASA missions, and information about the surfaces of Venus and the Galilean satellites will be acquired on future missions.

Earth orbital photography taken from the earliest manned flights during the Mercury and Gemini programs was used initially simply to compile or to correct structural maps of relatively small areas. As the value of these photographs became more widely known, however, they were applied to specific problems of regional tectonics. When Landsat images became available in 1972, the use of orbital imagery in tectonics and geodynamics rapidly expanded. Since that time, many important contributions to understanding of large-scale tectonics have been made by scientists using Landsat images: for example, the study of Iranian tectonics by Berberian (1974), the Guatemalan region by Muehlberger and Ritchie (1975), in which the significance of the Motagua Fault was pointed out, and in Mongolia by Okal (1977).

The most striking example, however, is the study of the tectonics of south-central Asia, a complicated and active region, but until recently a poorly understood one. The reasons for this lack of knowledge include the huge size and inaccessibility of the area. The use of Landsat imagery has overcome these problems, and our knowledge of Asiatic tectonism has been revolutionized by the work of Molnar and Tapponier (1977, 1978), Ni and York (1978), Tapponier and Molnar (1977), and York et al. (1976) among others. Using photographs such as that shown in Figure 5.3-1, it has been demonstrated that the apparent collision between India and Asia has not been taken up chiefly by shallow-angle thrusting, as proposed by Holmes, but instead largely by strike-slip faulting. The effect is analogous to the indentation of a plastic block by a rigid punch. This conclusion has major implications for plate tectonic theory and for geodynamics, since it implies large-scale plate deformation.

Figure 5.3-1. Landsat image of south-central Asia near the Indian-Eurasian plate boundary.

Another example is the map of global tectonic activity which was compiled using both published geological and geophysical maps and orbital photography by Lowman, Frey, Burke, and their collaborators (Lowman and Frey, 1979). The map was originally drawn as an aid to the interpretation of satellite geophysical data, but it is proving to be useful as a geological research and teaching aid. The map provides an objective and more comprehensive view of global tectonics than a typical plate boundary map. For example, this representation shows clearly that several plates are not completely circumscribed by recognizable boundaries, and that some smaller areas may not be plates but rather extremely broad zones of plastic deformation (see Figure 3.1-2b).

Several specific ways may be suggested in which orbital remote sensing can be used for research in geodynamics:

1. Landsat and Shuttle imaging systems can be used to carry out tectonic research of the sort already described.

2. Orbital imagery can be combined with surface and orbital geophysical data to study the correlation between crustal and mantle structure.

3. Orbital imagery of the earth can be compared with orbital imagery of other terrestrial planets to compare structural features, history, and evolution.

4. Greatly improved tectonic maps of seismically active areas can be compiled to study the relationship between seismicity and stress in the crust.

5. New types of orbital imagery, such as low-angle imaging radar and thermal infrared, can be used to construct improved tectonic maps of cratonic areas such as the North American mid-continent region.

6. The structural continuity between continents that existed before the present cycle of seafloor spreading can be studied and tested using orbital photography in conjunction with geological and topographic maps.

7. Orbital imagery can be used together with space-derived geodetic techniques to study the relation between strain accumulation and tectonic structure in a wide variety of tectonic environments, e.g., plate boundaries of different types, and to plan such geodetic operations.

8. The relationship between oceanic fracture zones and structures on continents can be investigated using orbital imagery together with hydrographic and marine geophysical data.

SECTION 6

IMPLEMENTATION

6.0 INTRODUCTION

In previous sections we have discussed the global, continental-scale, regional, and local studies that should be carried out to make full use of the capabilities of space technology for applications to geodynamics and earthquake studies. On the global scale, there should be a network of fixed VLBI stations and both lunar and Lageos laser ranging observatories to monitor polar motion and earth rotation, measure interplate motion, and serve as reference points for the roving network of mobile VLBI and satellite laser ranging stations. At the continental scale, the fixed observatories and some of the Moblas stations will measure the deformation of the plates to determine the stability of their interiors. At the regional scale, the mobile stations and some of the fixed observatories will monitor change in the strain field in tectonically active zones by extending local-scale ground-based geodetic measurements such as those carried out by the the U.S. Geological Survey and the National Geodetic Survey. Mobile stations will also be used to establish baseline measurements across a number of active faults in the world.

We have discussed in previous sections several particularly important and interesting regions that should be studied in the initial stages of the regional scale program: the western part of North America from the Colorado Plateau to the Pacific Coast and southward into northwestern Mexico; New Zealand, where the Pacific-Australian plate boundary is well exposed on land; the Fiji Island area, where an active spreading center exists; the western coast of South America, the best location for studying a subduction boundary; Alaska northward of the Aleutian Trench; and the Caribbean and Central America, where all types of plate boundaries are found in a small, important, yet poorly understood area.

In this section, we consider a plan for implementing these studies, and the associated milestones, decision points, and costs. In developing this plan, we have the used the following considerations:

(a) The limitations dictated by the availability of facilities and the lead times associated with hardware procurements;

(b) The role of NASA as a developer of space-derived technology and as a catalyst for the adoption of this technology by operational US agencies and those of other countries;

(c) The need for the continued development of advanced technology to serve the crustal dynamics requirements of the late 1980's in order to achieve a global monitoring capability for assessment and forecasting of hazards such as earthquakes.

(d) The validation and intercomparison of laser ranging and VLBI, the development of fixed and mobile facilities, and the establishment of improved polar motion and earth rotation systems.

6.1 FACILITIES AVAILABLE

The following is a summary of the current status of fixed and mobile facilities, and their projected status under current plans.

6.1.1 Fixed VLBI

VLBI facilities at Haystack, Massachusetts; Owens Valley, California; and Greenbank, West Virginia, are currently equipped with Mark III data acquisition systems (see Figure 6.1-1 and Appendix B). In late 1979, the Ft. Davis facility will be operational (Mark III) and with Westford (1981) will form the first element of the NGS Polaris Program (Carter, 1978). Later (1982) these facilities will be joined by a new NGS facility at Richmond, Florida. The facility at Onsala, Sweden (funded by DOD) will be operational in 1979. In support of requirements for the tracking of interplanetary spacecraft, the NASA Deep Space Network is equipping facilities in Madrid, Spain (DSS63), Goldstone, California (DSS14), and Canberra, Australia (DSS43), for VLBI using a data acquisition system equivalent to the Mark III. Currently, the design goal is a 50 cm polar motion capability.

6.1.2 Fixed Lasers

Satellite tracking facilities exist at GSFC (Stalas), Patrick AFB (Ramlas), and at SAO sites at Natal, Brazil; Arequipa, Peru; and Orroral Valley, Australia. Ramlas is capable of tracking low altitude satellites to a range precision of 10 cm, and Stalas to a range precision for Lageos of about 3 cm. In the current configuration, the SAO lasers are capable of about 10 cm for low-altitude satellites and for Lageos.

Lunar laser facilities are located at the McDonald Observatory at Fort Davis, Texas; Haleakala (Maui), Hawaii; and Orroral Valley, Australia. The McDonald Observatory is operational and provides a ranging accuracy of about 8 cm. The Hawaii and Australian facilities have achieved occasional lunar ranging, but are not yet operational. Haleakala has successfully tracked low-altitude satellites with ranging accuracies of 3-6 cm. In accordance with previous agreements, NASA plans to develop and locate a separate lunar/satellite facility (McDonald Laser Ranging System--MLRS) at the McDonald Observatory in 1981 as a replacement for the 107" telescope operations (see Appendix A).

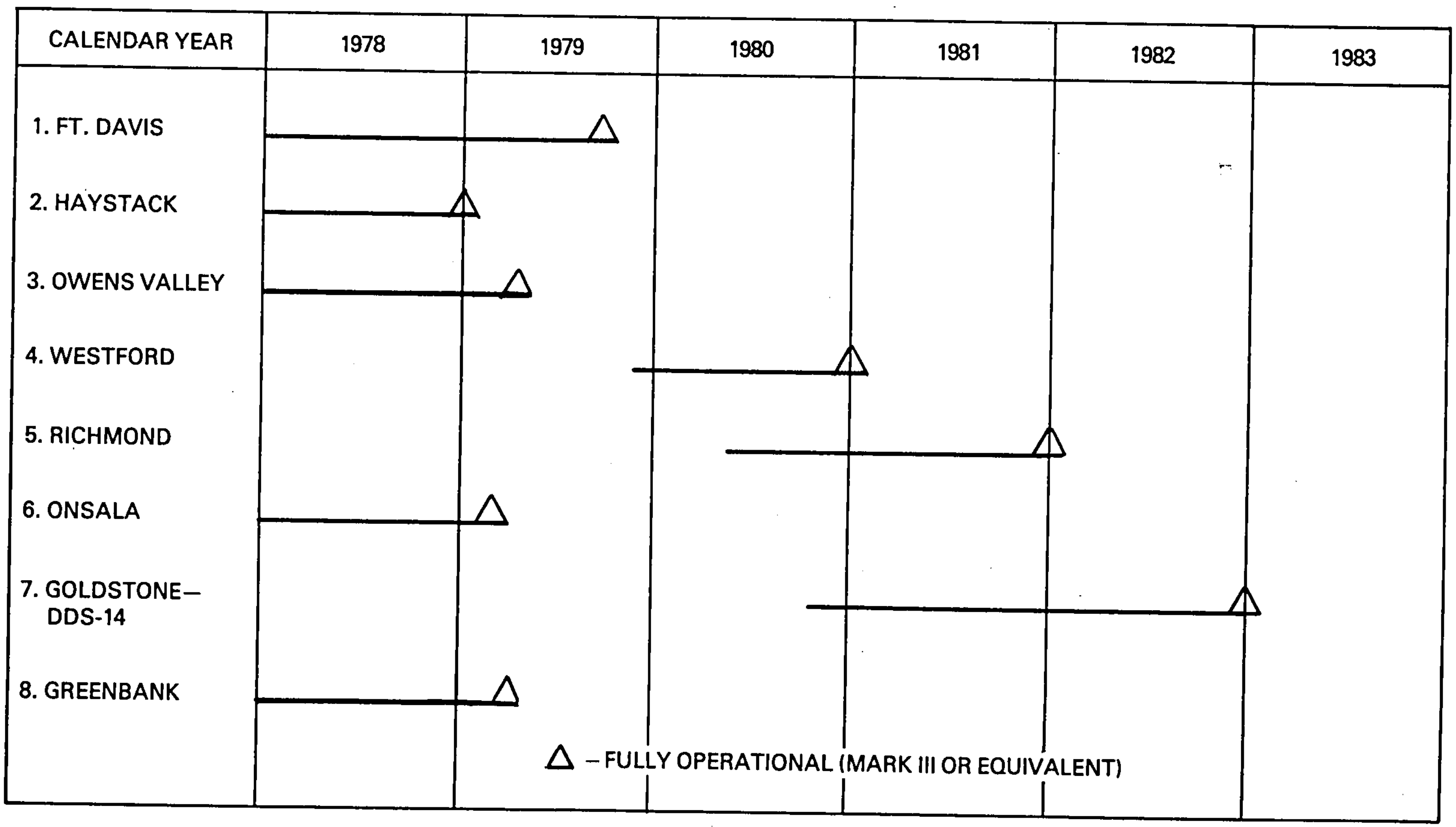


Figure 6.1-1. Fixed VLBI development schedule.

6.1.3 Mobile VLBI

A 9-meter transportable system (ARIES) has operated in California for the past several years. Currently, a prototype of a higher mobility system (using a 4m antenna) has been assembled and is undergoing performance and mobility tests. In 1980 these systems will be upgraded and completed. The 4m will be refurbished and a Mark III data system will be procured. Similarly, the 9m will be refurbished and the data system upgraded.

6.1.4 Mobile Lasers

NASA has plans for eight mobile lasers (Moblas). Three have been refurbished and were fielded to support Seasat tracking requirements. Five new Moblas stations are in fabrication and are to be deployed beginning in mid-1979.

A Transportable Laser Ranging Station (TLRS) capable of ranging to Lageos with an accuracy of 3 cm and employing the single photon ranging technique pioneered for lunar ranging is under development by the University of Texas (Silverberg, 1978). The TLRS is scheduled for field tests beginning in mid-1979 and will be available in October 1979.

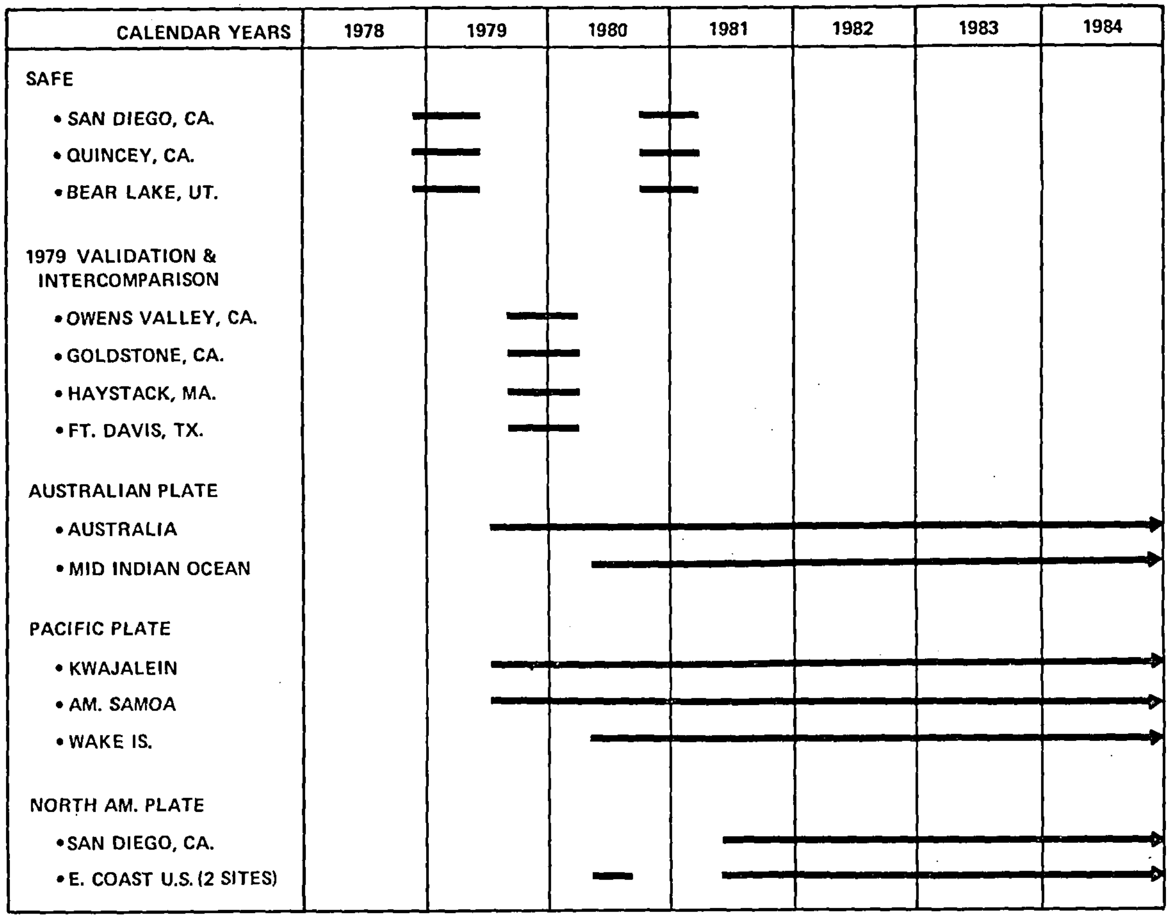


Figure 6.2-1. Moblas deployment schedule.

6.2 NASA GEODYNAMICS PROGRAM PLANS

Many of the activities within the current Geodynamics Program are relevant to crustal dynamics and are, in fact, the initial phase of the broader program described herein. Data acquired with fixed and mobile systems during the initial phase will provide discrete measurements of plate motion, plate deformation, regional deformation, and initial measurements of polar motion and earth rotation using VLBI and Lageos tracking.

The principal activities of the current geodyanmics program are:

1. San Andreas Fault Experiment campaigns in early 1979 and mid-1980;

2. Laser and VLBI validation and intercomparison experiment in 1979;

3. Acquisition of laser data for a Lageos investigations program starting in FY 79 and extending to FY 81;

4. Demonstration of fixed VLBI application to polar motion and earth rotation monitoring as a prerequisite for establishment of an operational system by the National Geodetic Survey in 1983.

6.2.1 Moblas

The schedule for the deployment and use of the Moblas stations is given in Figure 6.2-1. From January to May 1979, Moblas stations were deployed to Quincy, California, Bear Lake, Utah, and San Diego, California (Otay Mt.).

In May and July 1979, mobile VLBI stations will visit the Quincy and San Diego sites to verify the Moblas measurements.

As Figure 6.2-1 indicates, Moblas stations will be available in 1980 to support the North American plate deformation experiments.

6.2.2 Validation and Intercomparison

In October 1979, Moblas stations will be located at the Ft. Davis, Haystack, Owens Valley, and Goldstone VLBI sites for validation and intercomparison of the two techniques. The TLRS and the lunar laser at McDonald will participate in

the validation tests. These validation and intercomparison experiments are essential to the crustal dynamics program. The processing and analysis of the data will require about six months after acquisition, and this is projected to be completed in early 1981.

6.2.3 Lageos Investigations

The Lageos investigations will be supported by laser data from fixed and mobile systems. In addition, there is a need to maintain the Lageos orbit to support the ground-based laser measurements and provide long-term polar motion monitoring with satellite lasers for comparison with polar motion determined by VLBI and lunar laser ranging. To meet these requirements, Lageos laser tracking will be supported by Moblas stations at San Diego, California; Kwajalein Island; American Samoa; the Indian Ocean; Australia; Stalas; the SAO sites; Haleakala; the new laser facility at the McDonald Observatory, and the laser network in Europe. The TLRS will be available in late 1979 to support Lageos investigations in the US.

6.3 CRUSTAL DYNAMICS PROGRAM PLAN

In previous sections we have described the observations required for crustal dynamics studies. In Table 6.3-1 the time phasing for initiation of these studies is outlined.

6.3.1 Plate Motion Studies

The North American/Pacific plate motion sites are shown in Figure 6.3-1. The existing VLBI and laser sites in the continental United States, Haleakala, and Moblas sites in San Diego and the Pacific will be used for these studies. To support the requirement for VLBI measurements from Alaska and Hawaii to Goldstone, we propose to use a MIT-developed portable VLBI data system in conjunction with a USAF antenna located in Hawaii and the NOAA antenna in Alaska.

For the global studies, the existing VLBI, lunar laser, and Moblas sites will be used; however, additional facilities will be required (see Figure 6.3-2). It is planned to use the VLBI facility in Onsala, Sweden; a proposed facility in West Germany, lunar laser facilities in Grasse, France, and Delft, The Netherlands, as well as the DSN station in Madrid, Spain. New VLBI facilities would be established in Japan and Brazil.

6.3.2 Plate Deformation Studies

The site networks for the plate deformation studies are shown in Figure 6.3-3. For the North American, Pacific, and Australian plate studies the site locations and facilities are detailed in Figure 6.3-4. All of these capabilities are existing or planned.

The European plate stability studies will include the VLBI sites in Madrid, Spain (DSS063), Onsala (Sweden), West Germany, and Italy. Laser measurements will be provided by the lunar lasers in Grasse and Delft, and laser sites in France and Greece.

6.3.3 Regional Deformation Studies

The geographic location of regional study areas to be considered are indicated in Figure 6.3-5. Activities in these areas discussed in previous sections (Western North America, the Caribbean, New Zealand, the Fiji Islands, western South America, Japan, and Alaska) are initiated in 1980 through 1983. The Middle East and Far East areas are initiated in 1984. Beginning in 1983, the operational North American monitoring will be assumed by the NGS.

TABLE 6.3-1

GEODYNAMICS PLAN

	Initiation Date
• Plate Motion Studies	
• North American/Pacific Plates	1979
• Global	1982
• Plate Deformation Studies	
• Pacific	1979
• Australia	1979
• North America	1980
• Europe	1982
• Regional Deformation Studies	
• Western US & Mexico	1980
• Caribbean	1981
• New Zealand, South America, Alaska, Japan	1983
• Polar Motion & Earth Rotation	
• US Operational (VLBI) System	1983
• Gravity Field Surveys	
• Gravsat-A	1985
• Gravity Gradiometer (Gravsat-B)	1988
• Lageos II	1985
• Magsat-B	1984

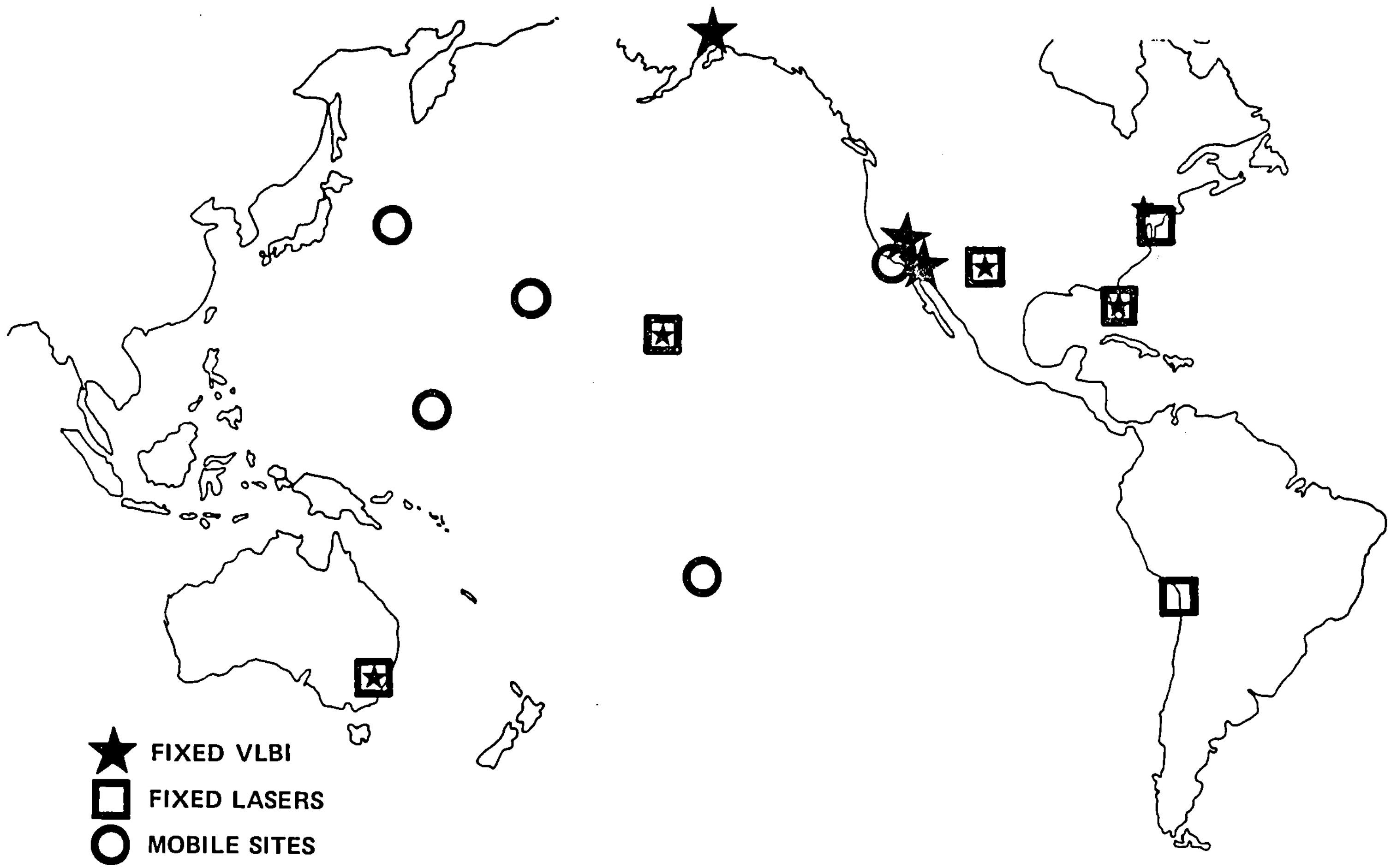


Figure 6.3-1. Proposed arrangement of stations in the Central Pacific for study of Pacific plate deformation and relative motion of North American and Pacific plates.

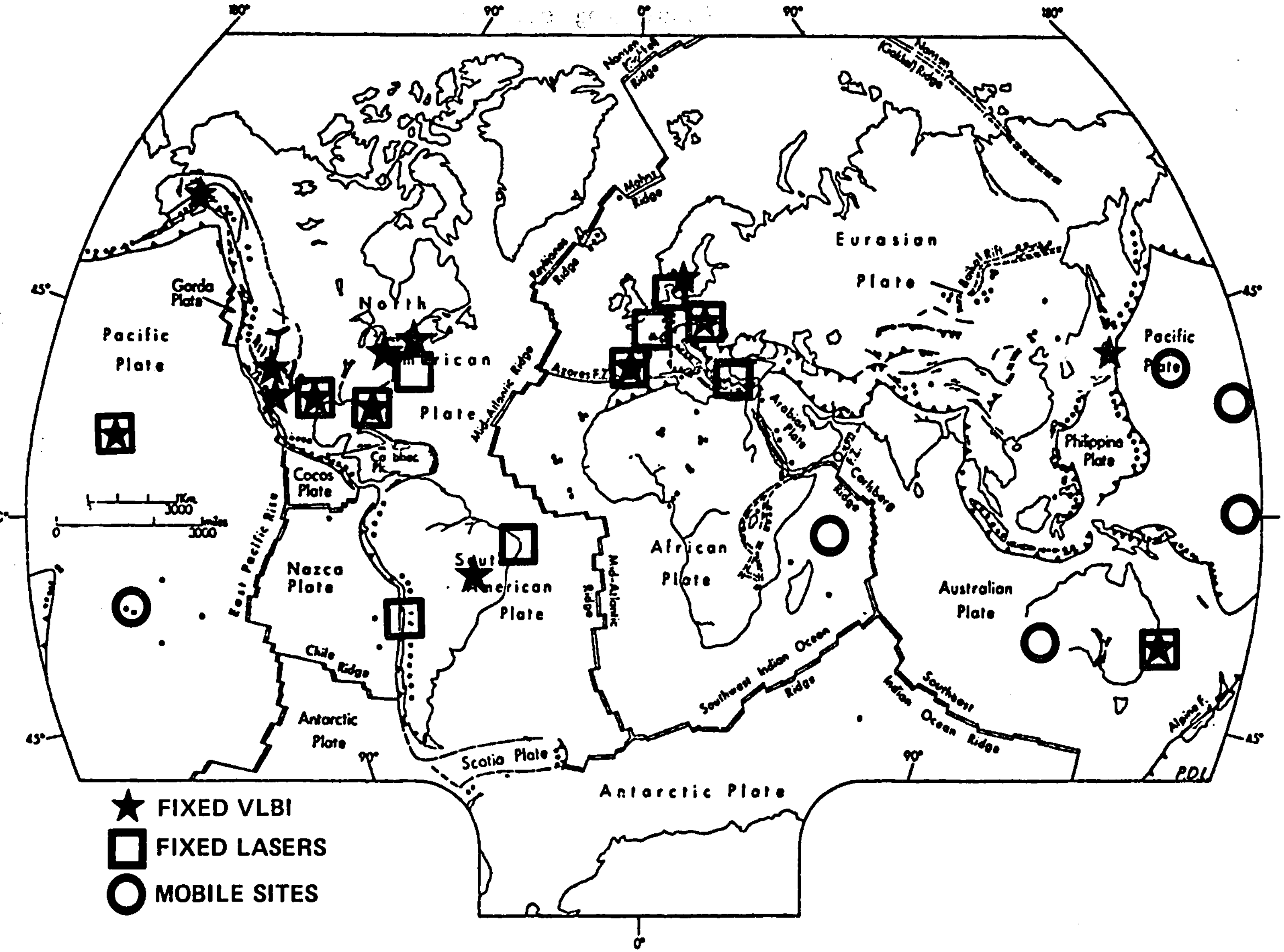


Figure 6.3-2. Network of VLBI and laser sites for global study of plate motion.

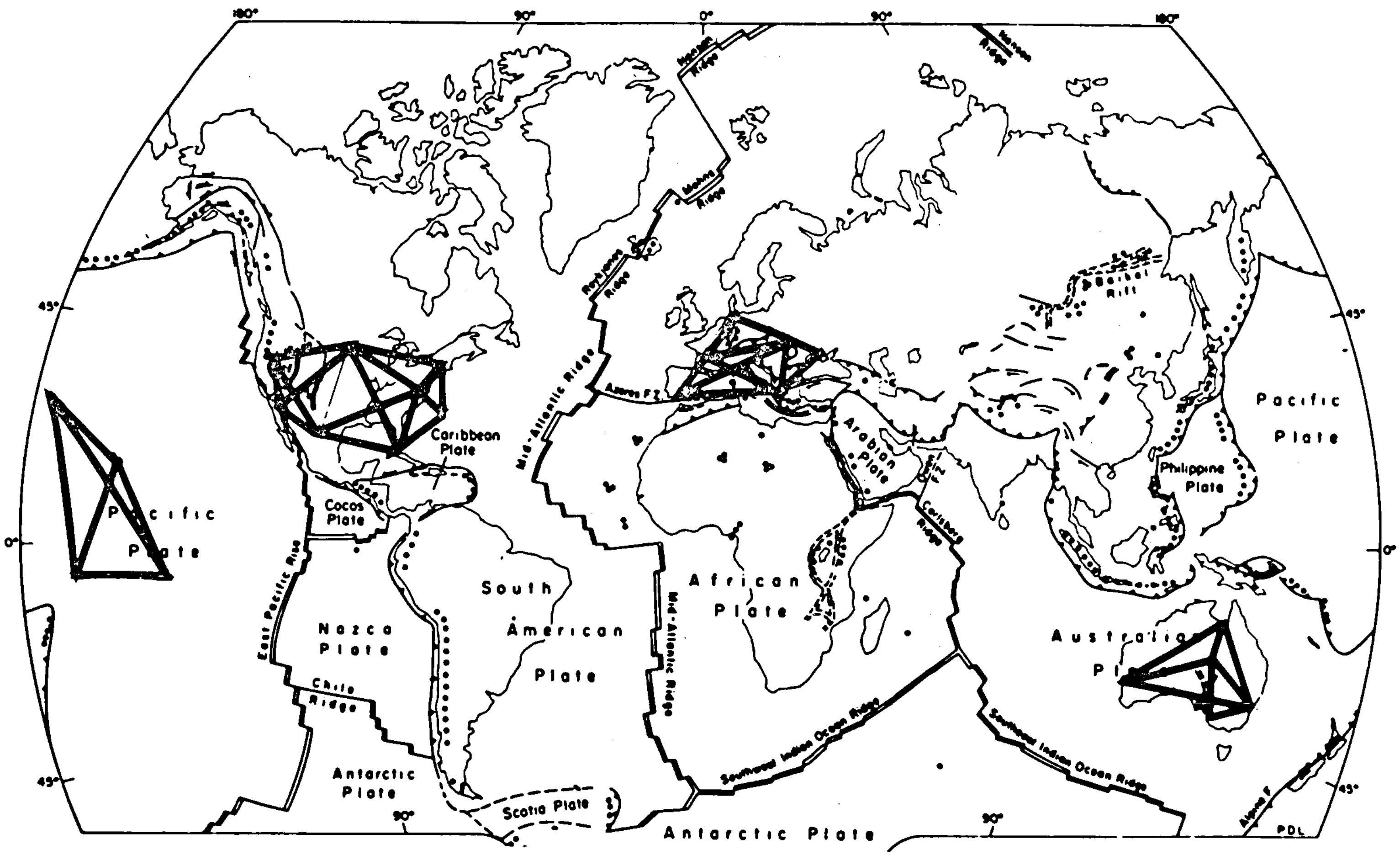


Figure 6.3-3. Site networks for study of plate stability.

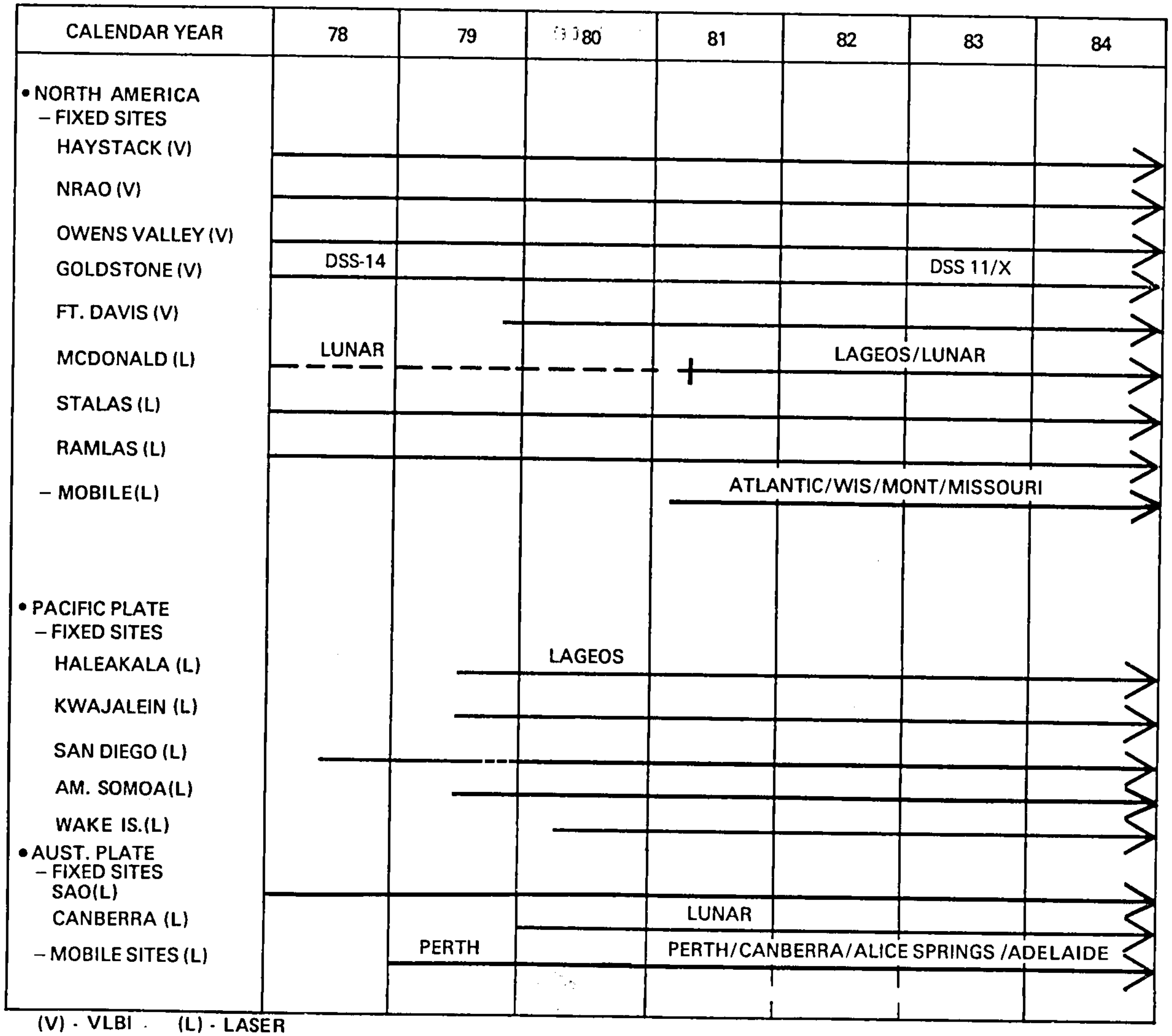


Figure 6.3-4. Locations and facilities for plate deformation studies: North America, Pacific, Australia.

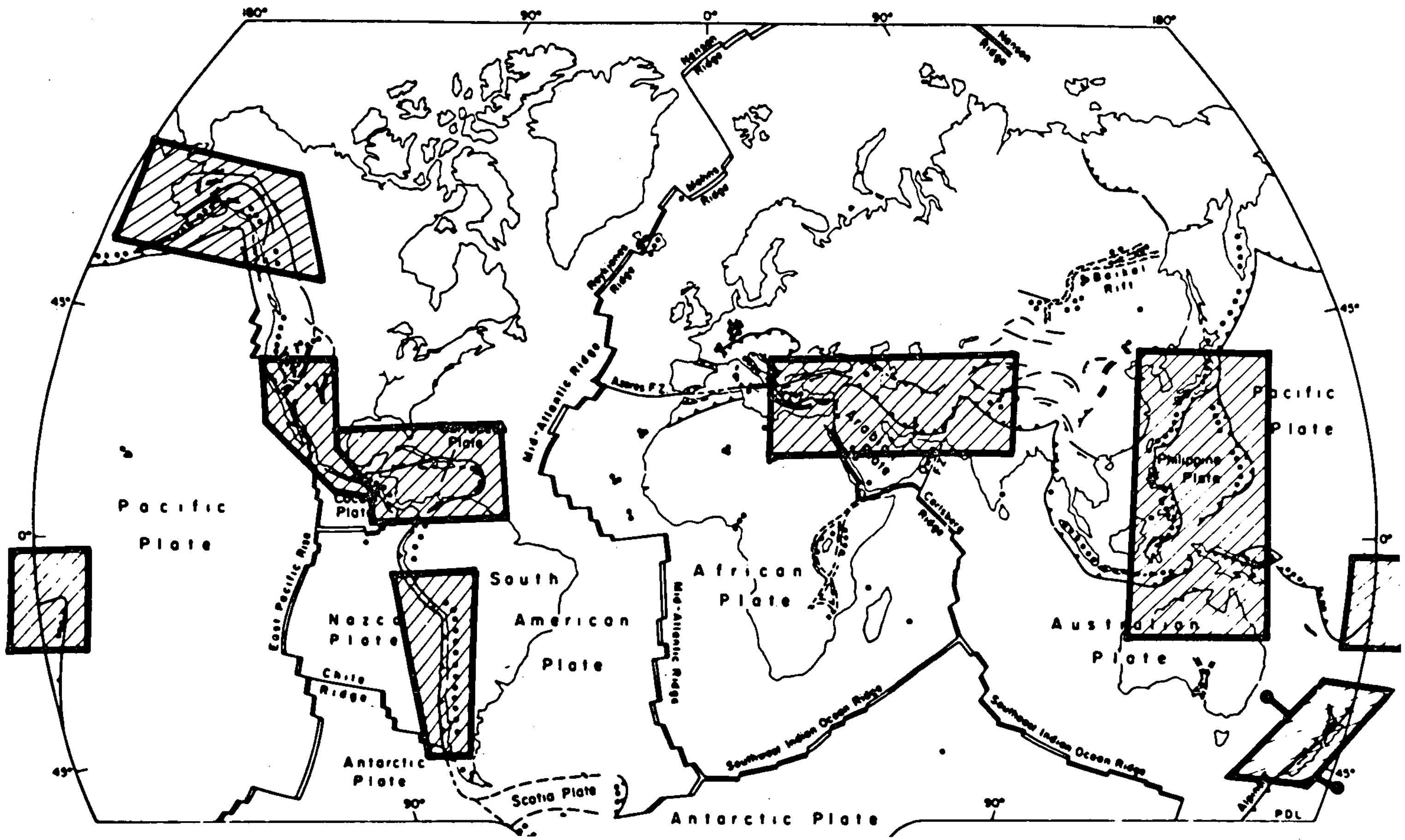


Figure 6.3-5. Location of areas considered for regional deformation studies.

The regional deformation studies are principally dependent on the use of mobile stations. While in some areas these mobile stations (such as VLBI) can make use of existing fixed facilities, they will generally operate independently. The number of sites and site visits per year required are as follows:

Region	Sites	Visits
North America	27	60
Caribbean	23	46
New Zealand & Fiji	12	24
South America	14	28
Alaska	5	10
Japan	13	26
Baselines	24	24
TOTAL	118	218

For an initial period lasting several years, both laser and VLBI data will be acquired at six of the western North American sites. The intercomparison of these data will provide increased confidence in the validity of the measurements and assure that no basic or systematic error has been introduced into the program.

The 24 baseline sites will be used in the early stages of the program to establish benchmarks at strategic locations around the world, where large continuous motions or large earthquakes might be expected. Possible sites for these benchmark measurements include the Motagua Fault in Central America, the North Anatolian Fault in Turkey, the Alpine Fault in New Zealand, and the Denali Fault in Alaska.

6.4 ANALYSIS OF MOBILE UNIT SITE COVERAGE

The maximum number of sites which can be occupied in a given time period by either mobile VLBI or mobile laser stations is critical to a determination of the number of stations required to support the crustal deformation studies, or alternatively, to where measurements can be made with existing systems.

At present, we have ten years experience with deployment of mobile stations. Moblas stations have been operated at five sites, and the 9m ARIES VLBI station has been operated repeatedly at about six sites in California. The deployment of Moblas laser stations to prepared sites has required about three months for transportation and checkout, followed by a two-month observing period. While it is anticipated that these times will decrease with additional experience, it is unlikely that a single Moblas station could occupy more than 2-3 sites per year. Consequently, we have concluded that Moblas units should be located at fixed sites after 1981, and should not be a factor in estimating mobile site coverage.

The 9m ARIES, working with the large antenna at Goldstone, has produced position determinations with two or three days of observations. More generally it has required 10 to 14 days to make a position determination, dismantle the antenna, move, and reassemble the 9m antenna at a second site. With the 4m ARIES (again working with the big dishes) it is hoped to achieve a site occupation rate of about one per week in later phases of the program.

We have estimated the average length of time required to set up, break down, and transport a mobile VLBI station between sites within the U.S. and have allowed for down time for maintenance and repairs. Since for VLBI observations it is necessary that two stations be operational, a greater down time can be expected. On the other hand, it is possible under certain situations to position one VLBI station for a series of observations and to move only the second station to new sites. In view of these considerations, we estimate that ten to twelve days for each domestic site, or about 30 sites per year, per VLBI station, is reasonable. For overseas sites, the difficulty of air or water transportation, the establishment of a temporary base for logistic support, and the increased frequency of movements over large distances make it prudent to reduce this estimate to about 20 site visits per station per year.

For the TRLS or similar "mini-mobile" single-photon laser ranging stations, the only available information on site visit times is from a simulation study by Bender et al. (1979). They assumed that eight fixed laser stations were operating around the world to maintain the Lageos orbit and that polar motion is provided by a network of fixed stations. Under these conditions, four days of Lageos ranging can provide an adequate determination of the station position. Allowing for unfavorable weather conditions, station setup and breakdown time, travel time between sites, and down time for repair and maintenance, estimates for the TLRS would be 30-40 site visits per year. We have chosen to use the smaller number.

More optimistic estimates of site visit times for mobile VLBI and "mini-mobile" laser stations have been suggested. These estimates assume ideal conditions, which in our experience are seldom achieved. The planned field tests of the TLRS in 1979 should help resolve the question of laser system mobility.

If a second Lageos satellite were in orbit, the increased frequency of Lageos passes using two satellites could substantially reduce the time for a position determination. This could amount to 3-4 days for TLRS, or about 10 more site visits per year.

6.5 REQUIREMENTS FOR MOBILE STATIONS

The requirements for mobile stations for plate motion and plate deformation studies are met with the existing and planned mobile stations.

In the 1979-1981 period, the existing 4m and 9m VLBI stations and the TLRS will be available to support the regional studies. In 1979, a few Moblas observations in western North America will be available as a result of the SAFE campaigns and the validation and intercomparison experiments. To support the requirement for approximately 218 site visits outlined in Section 6.3.3, additional mobile units would be procured by NASA in FY 1980 and FY 1982.

In arriving at requirements for mobile stations we have assumed that for studies of the deformation of plates in their stable interiors, one visit per year will be adequate, and that for regional strain measurements, two visits per year will suffice for the early phases of the program. Later, as our understanding of the amount of tectonic activity and deformation in these regions increases, a more frequent measurement cycle will be needed, since it is expected that sudden onsets of rapid movement will occur in some places.

If increased capability to measure position in shorter times than estimated in Section 6.4 is proven in field testing, this would be reflected in the planned program in five ways. In order of priority, these are:

1. The number of sites visited in the plate deformation studies would be increased;

2. The number of regional strain study sites visited by both VLBI and laser ranging stations would be increased in order to strengthen the intercomparison of measurements made by the two systems;

3. The number of visits per year to each plate deformation and regional strain site would be increased;

4. The number of regional strain sites to be visited would be increased;

5. The increased capability would decrease the impact on planned observations of diversion of stations to make measurements near the epicenters of large earthquakes that may occur in the regions under study.

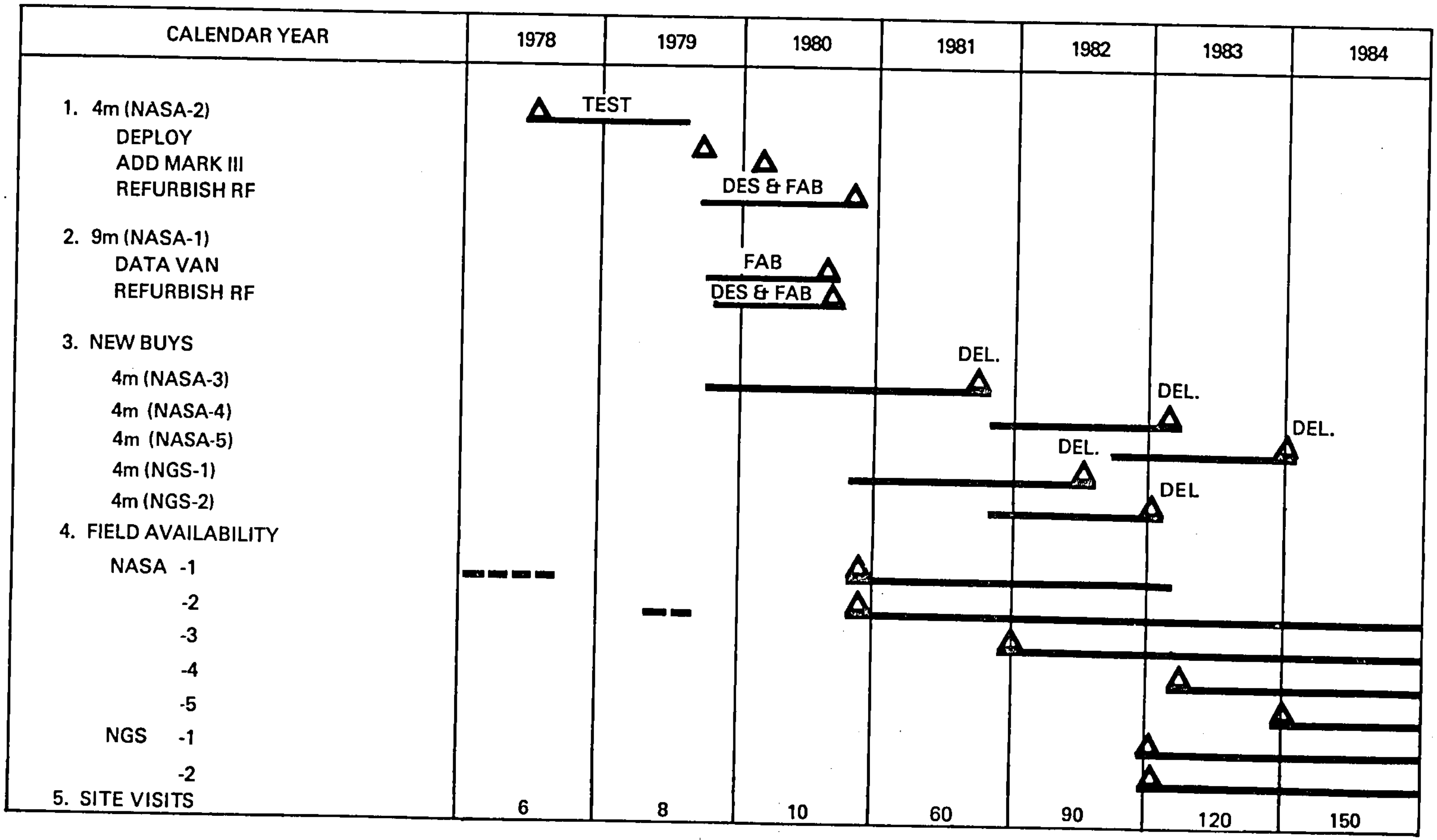


Figure 6.5-1. Mobile VLBI development schedule.

6.5.1 VLBI Development

The proposed mobile VLBI development schedule is outlined in Figure 6.5-1. The refurbished 9m and 4m (NASA-1 and -2) stations will acquire the needed North American site position determination in 1981 and 1982.

Starting in 1982, the new NASA VLBI station (NASA-3) will be deployed to support other elements of the Plan. In 1983, NGS stations will be operational. NASA-4 and NASA-5 will be available in 1983 and 1984, respectively. In 1983, NASA-1 will be retired and we will have available a total of five US VLBI stations with a total capability of 120 site visits per year (60 for the NGS stations in the US and 60 for the NASA stations deployed abroad).

6.5.2 Laser Development

The satellite laser ranging development schedule is outlined in Figure 6.5-2. The performance of Moblas systems varies from the 3-5 cm achieved with Moblas 1 through 3, to 10 cm for Moblas 4 through 8. Studies underway are expected to provide design modifications to improve Moblas performance to 1-2 cm. The new design will be tested in a Moblas in 1979. If successful, the remaining Moblas systems will be modified sequentially by late 1980, either at the deployed sites or by returning to GSFC.

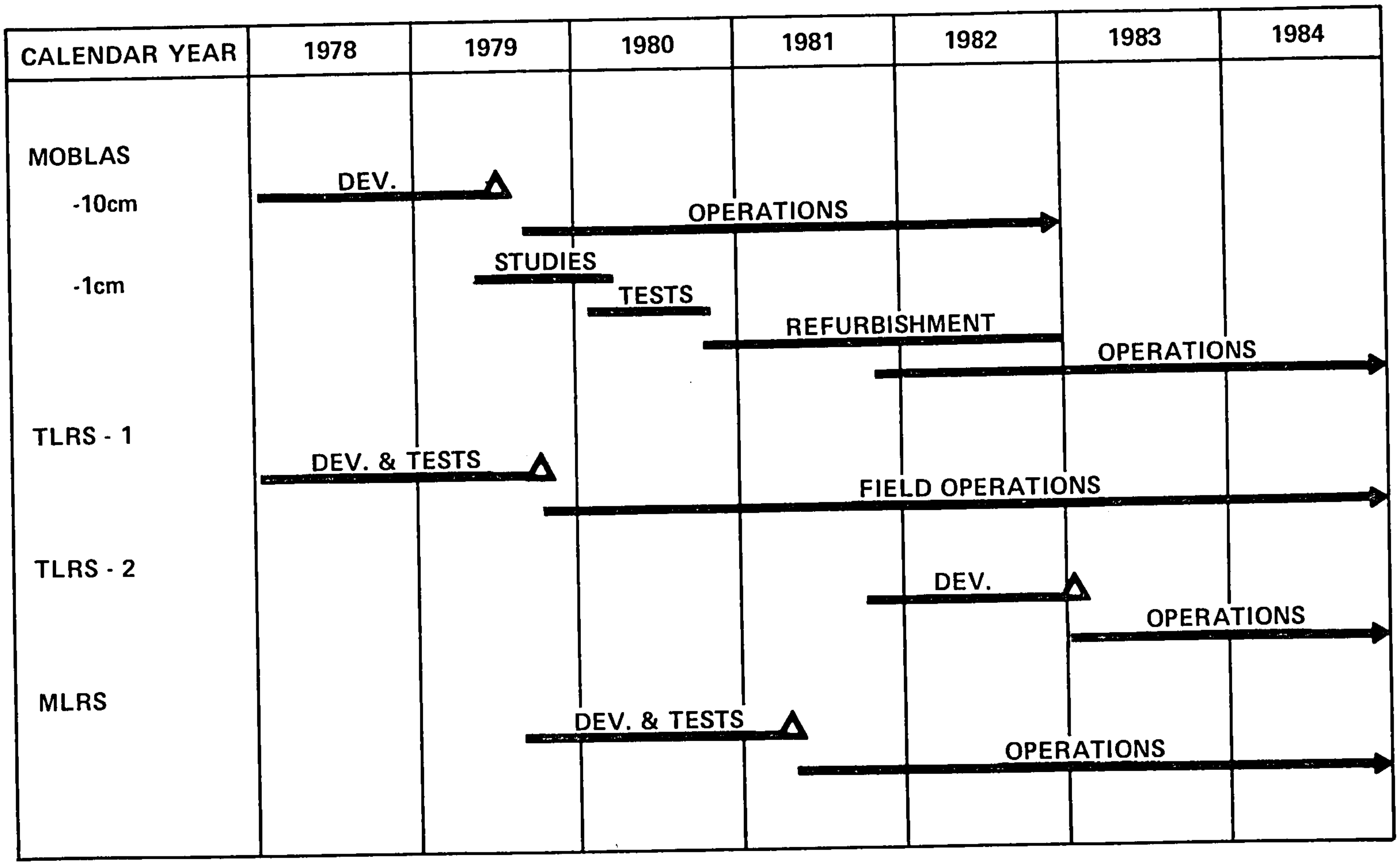


Figure 6.5-2. Satellite laser ranging development.

6.6 ADVANCED TECHNIQUE AND SYSTEM DEVELOPMENT

Several concepts have been suggested for rapid and accurate (few centimeters) position determination for points spaced 20-100 km apart. The potential for cost savings on a per site basis is substantial, perhaps as much as an order of magnitude. However, none of these concepts has been developed to a point where either its performance or cost benefits can be accepted with the assurance needed to warrant consideration as primary elements of the initial crustal dynamics program. The concepts, which group into three classes, involve the acquisition of signals from the Global Positioning System (GPS), laser ranging from a space platform, and very small laser systems transported by a van and deployed on a tripod.

Each of the concepts has sufficient merit to warrant development at least to the point where intercomparisons can be made and performance and cost of operational systems estimated. In developing the implementation plan we have provided for these advanced techique developments and have incorporated decision points when trade-offs can be assessed to determine the need for continued development. This plan is summarized on Figure 6.6-1. Detailed comments on each of the three classes of techniques are given below.

6.6.1 GPS Systems

Doppler tracking of near-earth satellites has been used extensively and has provided the relative positions of fixed sites to a meter or better. More recently, it has been reported that accuracies of a few decimeters have been achieved. Use of the GPS, the follow-on satellite system, is advantageous in that with the full complement of 24 satellites (planned for the late 1980's) a minimum of four satellites can be observed simultaneously at any one time. Simulation studies suggest that with simultaneity of observations and several electronic improvements, accuracies better than 10 cm should be achieved (Anderle, 1978). DMA is currently supporting the development of this concept with tests planned for 1979. At that time, at least six GPS satellites are expected to be in orbit.

Another technique is to use the L-band transmissions from the GPS satellites instead of quasar signals (MacDoran et al., 1978; MacDoran, 1979). With the stronger signals from the GPS and the very much narrower bandwidth, the measurements would be simpler and require less observation time. The differential mode used with VLBI has the advantage that the deleterious effects of satellite ephemeris error and other uncertainties are minimized. However, it may be

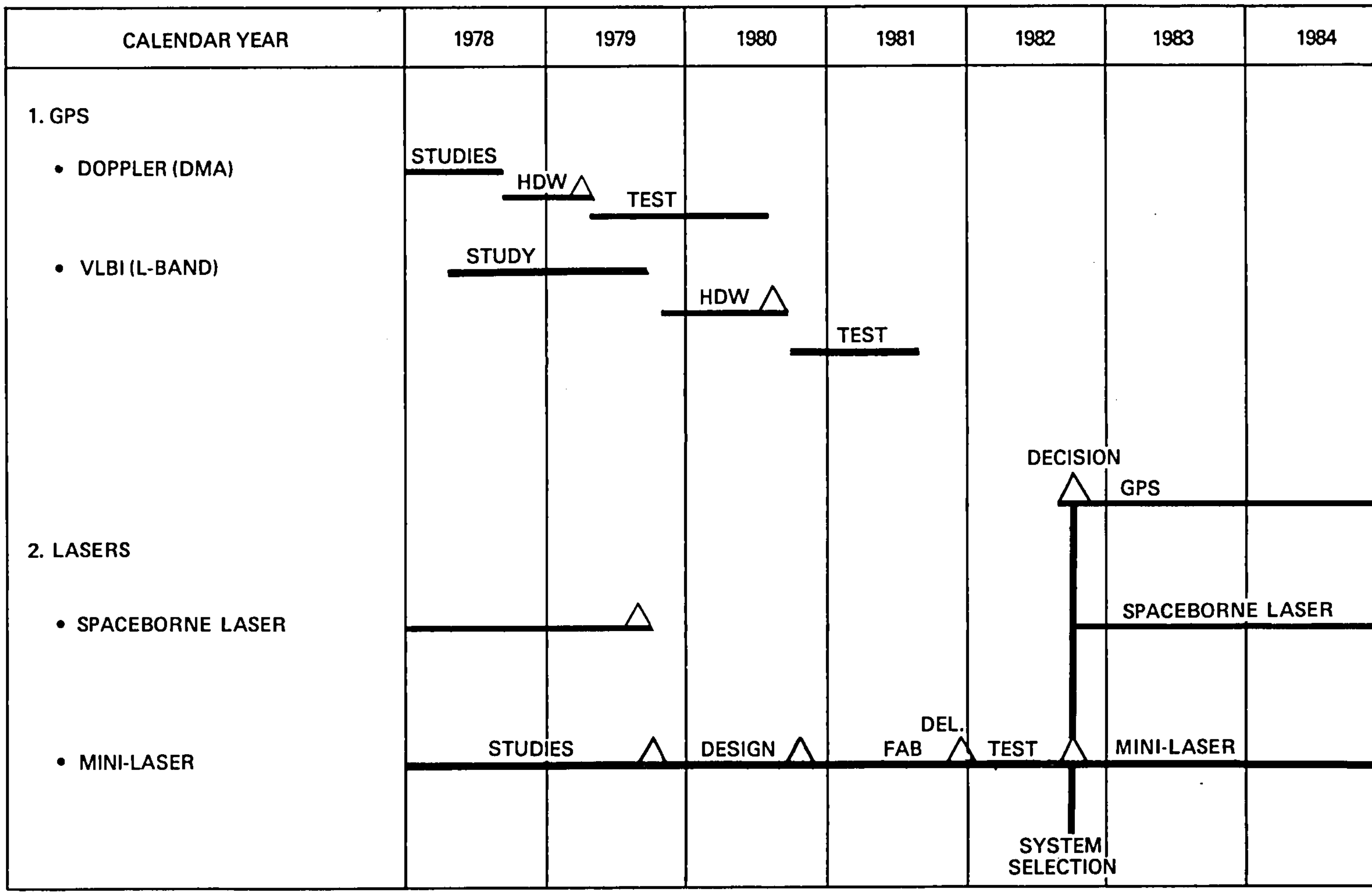


Figure 6.6-1. Advanced techniques for local strain studies.

necessary to refine the GPS ephemerides to achieve the 1-2 cm accuracy over 500 km baselines. One suggestion is to use the large fixed VLBI antennas to reference each GPS to the quasars. This satellite-VLBI concept is under development and should be ready for testing in 1980.

The third GPS concept involves the use of a coded train of timing pulses (Counselman and Shapiro, 1978). This would require modification to the GPS design to include a small, low-power, special-purpose transmitter. While it appears that this is feasible with the next group of GPS (to be in orbit by the mid-1980's), agreements with DoD for the modification would have to be implemented by late 1981.

Both the doppler and L-band VLBI concepts can be tested through field trials using existing unmodified GPS. Trade-off studies of the GPS approaches are expected to continue to 1981.

6.6.2 Shuttle Ranging Experiment

A spaceborne ranging system using a laser has been proposed as an economical and effective means of routinely monitoring crustal strain on a regular basis in most of the critical seismically active areas of the world. By the late 1980's, it is reasonable to assume that we will be prepared to support a global demonstration and verification of earthquake prediction models. Thus the requirements for continuous routine observations might involve such a large number of ground points that spaceborne laser ranging, with its inexpensive and passive ground reflectors, would be the most cost-effective approach.

Extensive simulations have been carried out for the spaceborne laser ranging system. The results indicate that the relative locations of the retro-reflector targets can be recovered in three dimensions with a formal standard error of about 2 cm (Smith, 1978; Smith and Tapley, 1979).

The spaceborne ranging development would be initiated in FY 1983 with the first flight occurring in late 1986. Prior to initiation of hardware fabrication, the detailed design costs and performance will be compared with the GPS and mini-laser concepts and a decision made to proceed or to redirect the work.

6.6.3 Mobile Ground Systems

The TLRS and the mobile VLBI stations we plan to use are indicative of the current state of development of mobile systems. Further advances in VLBI mobility are likely to come from the GPS-related developments. Satellite laser ranging advances are believed possible and studies are underway, both in the US and Germany, of a very compact mini-laser system which would be competitive with the radio interferometry approaches.

We believe studies of these mini-laser concepts should be conducted. In late 1979, test results will be available from use of the 4m VLBI and the TLRS, and a decision can be made of the need and appropriateness of carrying the mini-laser through development and test.

6.6.4 Future Systems

By the mid-1980's all the techniques currently envisioned for making crustal deformation measurements on scales of tens to hundreds of kilometers will have been demonstrated and assessed in terms of performance and costs. This will provide the basis for selection of system(s) for continuation of a global program through at least 1990.

An obviously desirable extension of the precise position measuring systems discussed in this document is to develop procedures for making similar measurements between benchmarks on the floor of the oceans. This would allow measurement of plate movement and deformation at ocean spreading centers, and on both sides of many subduction zones. The main problems involved in such measurements are the stability of the bench-marks, the presence of signal path length variations between the surface of the ocean and the bottom, and providing an adequate platform on the ocean surface. Clearly, the technology for position measurements must be highly advanced before such an extension would be practicable. Development work in this area will be considered in the later stages of the program described here.

6.7 DATA MANAGEMENT AND ANALYSIS

In the NASA Crustal Dynamics Program data of various types will be acquired from many sources. These data will be freely available to others, and will be provided to a large group of investigators (perhaps 100 or more) selected through various processes to conduct studies.

An extensive data management system will be essential to the orderly acquisition, processing, dissemination, and archiving of data. Considerable care will have to be exercised in scheduling site visits in verifying the quality of the data sets and ascertaining that the data are readily available to investigators.

6.7.1 Data Acquisition

Site visits by mobile systems and observation periods by fixed systems will be scheduled sufficiently far in advance to assure a coordinated program of observations with other activities such as the acquisition of conventional types of ground-based data. Flexibility will be maintained to alter this schedule in order, for example, to respond to the prediction or occurrence of an earthquake or to concentrate observations in areas where rapid crustal movements are indicated by earlier measurements.

At each site local surveys will be made on a regular basis to verify the stability of the site. These data will be considered part of the data record. In addition, all data acquired by participating investigators will be formatted and archived with the primary data.

Polar motion and UT1 data from Polaris and the DSN (when available) will be included as part of the data base.

For selected key areas, historical data such as seismograph records, tiltmeter recordings, gravity, survey traverses, etc., will also be formatted and archived.

6.7.2 Data Processing

Processing of VLBI and laser data will generally be performed at central data centers. In some cases, the processing will be accomplished at the data acquisition facility. Central VLBI processing capabilities will be located at JPL (mobile VLBI) and at GSFC (fixed VLBI). All

Moblas data will be processed at GSFC. Initially, the TLRS data will be processed by the University of Texas. Later, as TLRS becomes operational, these data will also be processed at GSFC.

The current facilities for VLBI and laser processing facilities at JPL and GSFC are inadequate for the crustal dynamics program and will have to be expanded. While these data are not perishable, a continuous and routine data flow is essential. Typically, the Lageos orbits, polar motion and earth rotation, laser ranging data, and VLBI-derived coordinates are planned to be made available within three months of the observations. Other data, such as point-to-point distances, should be made available at least within the time interval of site visitations.

6.7.3 Data Analysis

The analysis of these data will be conducted by Principal Investigators selected in response to a NASA Announcement of Opportunity in 1981 and through separate agreements with participating countries. Funding for US investigators is included in the budget estimates. Other investigators selected and funded by the USGS, NGS, or the NSF will be provided data and will become participants in the program.

6.7.4 Data Archives

Since many of the studies will depend on historical data, data sources other than the position determinations, and a long-term data base of crustal deformation measurements, it is essential that a central data archive system be established and maintained. This data system will service the selected investigators and other interested groups.

Data acquired by this program will be archived at a location to be selected. The National Space Science Data Center (NSSDC) at GSFC and faciliites operated by NOAA are possible candidates.

As part of this program and in conjunction with other studies being conducted by NASA for establishment of an interactive Applications Data System (ADS), studies will be performed of the data requirements for crustal deformation (and more generally, geodynamics) investigations. The eventual goal of these studies is to provide a basis for an information retrieval system whereby NASA-funded and other investigators can have ready access to data files in the several agencies and other locations.

6.8 INTER-AGENCY AND INTERNATIONAL PARTICIPATION

Under this plan, NASA will develop and demonstrate new space-derived technology for application by other Federal agencies and other countries. It is important to emphasize that close coordination with users is essential for systems development and application. NASA and the agencies mentioned below maintain contact in geodynamics-related programs through liaison membership in each agency's advisory committees, relevant committees of the National Academy of Sciences, and through an Interagency Coordinating Committee for the Application of Space Technology to Geodynamics (ICCG); the activities of this Committee are described in a recent Federal program plan (NASA et al., 1979).

6.8.1 Federal Agency Participation

The major participants in this cooperative approach are the National Geodetic Survey (part of NOAA's National Ocean Survey), the US Geological Survey, the National Science Foundation, and the Defense Department's Defense Mapping Agency. In this section we discuss briefly the activities being carried out by these agencies that are relevant to the NASA Crustal Dynamics Program. Tables 6.8(a)-(d) show in outline form the specific activities in the development and operation of VLBI systems, laser ranging systems, and new technology for local position determination.

National Geodetic Survey

NGS has the national responsibility for geodetic operations within the United States. NGS conducts extensive first-order surveying and leveling, maintains benchmarks, and carries out other operations needed to preserve the national control networks. NGS maintains a research program devoted to improving methods of horizontal and vertical surveys, and is establishing a large-scale data management system for geodetic data of all kinds. A major effort is the readjustment of the North American Datum, planned for the period 1979-84.

NGS also is responsible for the United States' participation in the worldwide system of polar motion monitoring by astrometric methods. A decision was made in 1977 by NGS to phase over to a VLBI system (Polaris) to replace the optical

TABLE 6.8(a)

ACTIVITIES IN FIXED LASER OBSERVATORY OPERATIONS

NASA	1. Operation of Stalas, Haleakala, McDonald, and SAO stations. 2. Conversion of Haleakala and McDonald to satellite ranging. 3. Data reduction, analysis and distribution.
NGS	Data analysis
USGS	Basic research
NSF	Basic research
DoD	Data analysis
Foreign	1. Contribution of foreign laser ranging stations. 2. Data analysis 3. Basic research

TABLE 6.8(b)

ACTIVITIES IN FIXED VLBI OBSERVATORY OPERATIONS

NASA	1.	Development of advanced systems.
	2.	Transfer of technology to NGS for Polaris.
	3.	Use of Polaris data in geodynamics program.
	4.	Coordination of international observations network for plate motion monitoring.
	5.	Processing and analysis of data.
NGS	1.	Equipping of Polaris stations.
	2.	Comparison and evaluation of Polaris results.
	3.	Provide Polaris polar motion data for use by outside investigators.
USGS	1.	Support of VLBI wideband data collection development at MIT.
	2.	Support of geophysical research.
NSF	1.	Support for Fort Davis radio antenna.
	2.	Support of portable advanced data equipment (Mark III) for Onsala, Sweden.
	3.	Support of geophysical research.
DoD	1.	Logistical support for Polaris operations at Richmond, Florida.
	2.	Support of VLBI equipment for Onsala, Sweden.
	3.	Continue publication of earth rotation parameters and provide CEI results for VLBI comparison.
Foreign	1.	Contribution of foreign VLBI stations.
	2.	Data analysis.
	3.	Basic research.

TABLE 6.8(c)

AGENCY ACTIVITIES IN MOBILE LASER RANGING AND VLBI STATION OPERATIONS

NASA	1.	Completion and testing of mobile laser systems.
	2.	Construction and testing of mobile VLBI stations.
	3.	Feasibility and design studies of a mini-mobile station concept.
	4.	Initiation of measurements at North American sites, expanding to the Caribbean and elsewhere.
NGS	1.	Mobile VLBI station operations (beginning in 1983).
	2.	Local gravity and surveying operations to support mobile sites.
USGS	1.	Site selection.
	2.	Recommend diversion of facilities to study post-seismic crustal movements.
	3.	Support of geophysical research.
NSF	1.	Support of geophysical research.
Foreign	1.	Concept and design studies of mimi-mobile laser ranging systems.
	2.	Foreign observations: cooperation in site selection, field operations, and data analysis.
	3.	Basic research.

TABLE 6.8(d)

ACTIVITIES IN STUDY OF IMPROVED LOCAL GEODETIC METHODS

NASA	Concept and design studies of space laser ranging, doppler, and GPS/VLBI methods.
NGS	1. Studies of doppler and GPS systems. 2. Definition of requirements for geodetic surveying.
USGS	Definition of requirements for crustal motion monitoring.
NSF	Basic research; definition of requirements.
DoD	Responsible for GPS; approval of system modification.
Foreign	Concept and design studies of mini-mobile laser ranging station.

systems that have been used virtually unchanged since the turn of the century. The Polaris system will consist of three dedicated radio antennas at Westford (Massachusetts), Fort Davis (Texas), and Richmond (Florida). These will be equipped with Mark III VLBI electronics and will use quasar sources. Almost all the costs for development and validation of the VLBI systems have been borne by NASA.

The Polaris stations will be crucial to the crustal dynamics program in two ways. First, polar motion and earth rotation will be determined by the Polaris network at an accuracy of a few centimeters with averaging times of a few days or less. These parameters are necessary in order to determine the precise position of mobile station sites. Second, the Polaris observatories will be used as reference stations for the mobile VLBI facilities. The few hours per month that can be allocated to geodynamics work on the radio astronomy and DSN antennas will probably be insufficient for carrying out an intensive field operations program of the kind discussed in this plan. Modification of the Goldstone DSS-11X antenna to aid in this work is included in the NASA budget. NGS will also conduct local site surveys and make gravity observations at the mobile station sites and the fixed observatories, as they have already done for McDonald Observatory and the LURE Observatory on Maui.

U.S. Geological Survey

In addition to having lead agency responsibility for the US Earthquake Hazard Reduction Program, the USGS is conducting in its Geologic Division a broad program of research and development in geological and geophysical sciences. These include mineralogy, petrology, solid-state geophysics as applied to rock-forming materials, and marine geology and geophysics. Almost all these programs are relevant in one way or another to geodynamics.

Observation of crustal movements in earthquake-prone areas is an important part of the Earthquake Hazard Reduction Program (USGS, 1979). The USGS has funded development of a multi-wavelength geodimeter now in routine use to monitor creep and crustal movement in California and has a program of geodetic resurveying in California in cooperation with NGS and with local governments. Part of the USGS in-house and extramural research programs is devoted to physical modeling and analysis of crustal motion data.

National Science Foundation

NSF funds basic research in geology, geophysics, and geochemistry, and at present their support of geodynamics research is channeled through these programs. It is anticipated that as a result of new data obtained under the NASA program described in this document, a significant increase in requests for research support will be generated within the university research community. NSF provides partial funding for geodynamic observations at the National Radio Astronomy Observatory at Greenbank, West Virginia.

Defense Mapping Agency

DMA is responsible for mapping, charting, and geodetic operations for the Department of Defense. Because of its expertise and because of the possible national defense significance of precise gravity and position data, its active cooperation with NASA has been of importance since the beginning of the National Geodetic Satellite Program in the early 1960's. The US Naval Observatory has the US operational responsibility for earth rotation monitoring through the IPMS. DoD is planning to provide logistics support for the NGS Polaris operations at Richmond, Florida.

Since the Global Positioning System (GPS) is a DoD program, DMA will play a key role in defining the need for application of GPS for civilian uses, both for practical surveying and for geodynamics research.

6.8.2 International Participation

It is clear that improvement in understanding dynamic processes within the earth - including earthquakes - requires a global rather than a purely domestic program. International participation in the NASA Crustal Dynamics Program is essential to accomplishing its objectives. This participation will take several forms:

1. Cooperative programs with governments of other countries to operate NASA's mobile laser ranging and VLBI stations at foreign sites;

2. Coordination between NASA, NGS, and the governments of countries with their own mobile laser ranging or VLBI stations to make most effective use of the total complement of mobile stations;

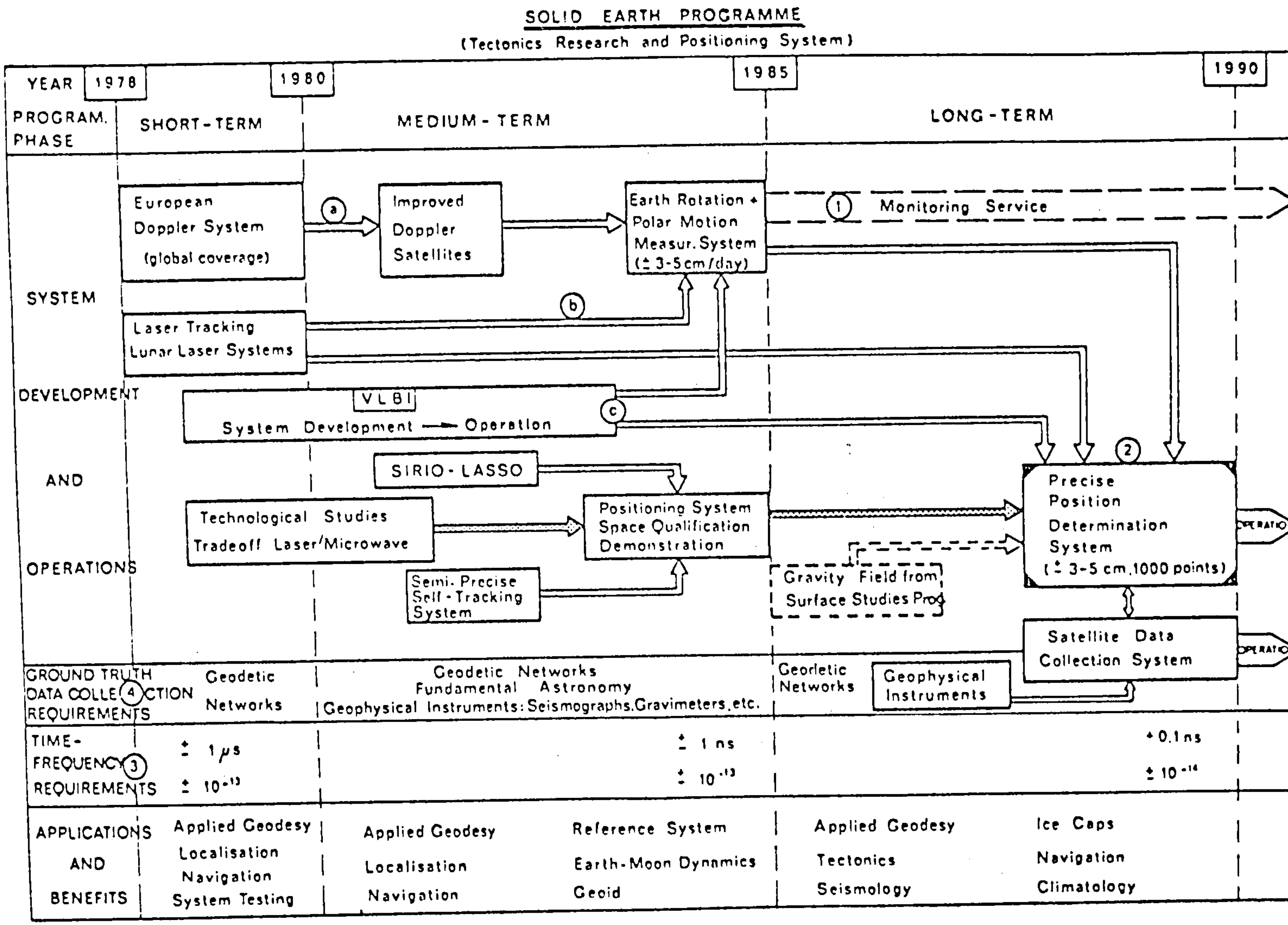


Figure 6.8-1. Solid-earth program under consideration by the European Space Agency.

3. Exchange of data from US fixed and mobile stations with scientists of other countries;

4. Encouragement of other countries to establish fixed observatories and to procure mobile laser ranging or VLBI stations for participation in the global data acquisition and analysis program;

5. Encouragement of an international body to oversee program planning, coordination of activities, and exchange of data from all fixed and mobile facilities.

A description of the present (mid-1979) status of discussions concerning international projects is given by NASA (1979).

The European Space Agency is presently formulating its own program of application of space technology to geodesy and geodynamics. A workshop on Space Oceanography, Navigation, and Geodynamics was held in West Germany in January, 1978, to outline a European program not only in geodynamics, but in related subjects as well (European Space Agency, 1978). Figure 6.8-1, from Kovalevsky et al. (1978), shows the preliminary overall schedule for these proposed activities. The aspects of primary interest to the NASA geodynamics program are the establishment of a European system for monitoring polar motion and earth rotation and the development of systems for crustal motion monitoring. Specific recommendations for a European program in earthquake prediction research, including application of space technology, were made at a Symposium on Earthquake Prediction Research in March, 1979 (European Space Agency, 1979). Coordination of planning is being accomplished at present through the exchange of program planning documents and discussions between key personnel on both sides.

The International Association of Geodesy, one of the constituent associations of the International Union of Geodesy and Geophysics, has several active commissions and study groups, one of which is the Commission on Recent Crustal Movements (CRCM). NASA, the CRCM, and the USGS jointly sponsored a symposium on recent crustal movements at Stanford University during the summer of 1977 at which there was informal discussion of the importance of space technology in future developments in this area. It is expected that CRCM will play an important role in international planning and coordination of programs.

The Bureau International de l'Heure now serves as a center for analysis and distribution of data on polar motion and earth rotation acquired by the International Polar Motion Service. BIH has also agreed to distribute polar motion data from the lunar laser ranging observatories (EROLD) through a Cospar-sanctioned working group. It is logical to expect that BIH might become involved in a similar way in the forthcoming global geodynamics program.

The Interunion Commission on Geodynamics is sponsored by the International Union of Geodesy and Geophysics and the International Union of Geological Sciences through the International Council of Scientific Unions. The ICG is planning its program for the 1980's to follow the successful International Geodynamics Project, which terminates in 1979.

Preliminary informal discussions have been held between NASA scientists and geophysicists in several other countries: for example, Canada, Mexico, Peru, and New Zealand. A workshop on applications of space technology to geodesy and geodynamics was held in August 1978, under the sponsorship of the Institute of Geophysics in Lima, Peru. This workshop gathered together geodesists and geophysicists from South American and Central American countries to inform them of planning activities within NASA and elsewhere, and laid the groundwork for operations with mobile and fixed stations in Latin America as part of the program described here. IUGG has applied for a grant from UNESCO to sponsor similar workshops in other parts of the world during the period 1979-84.

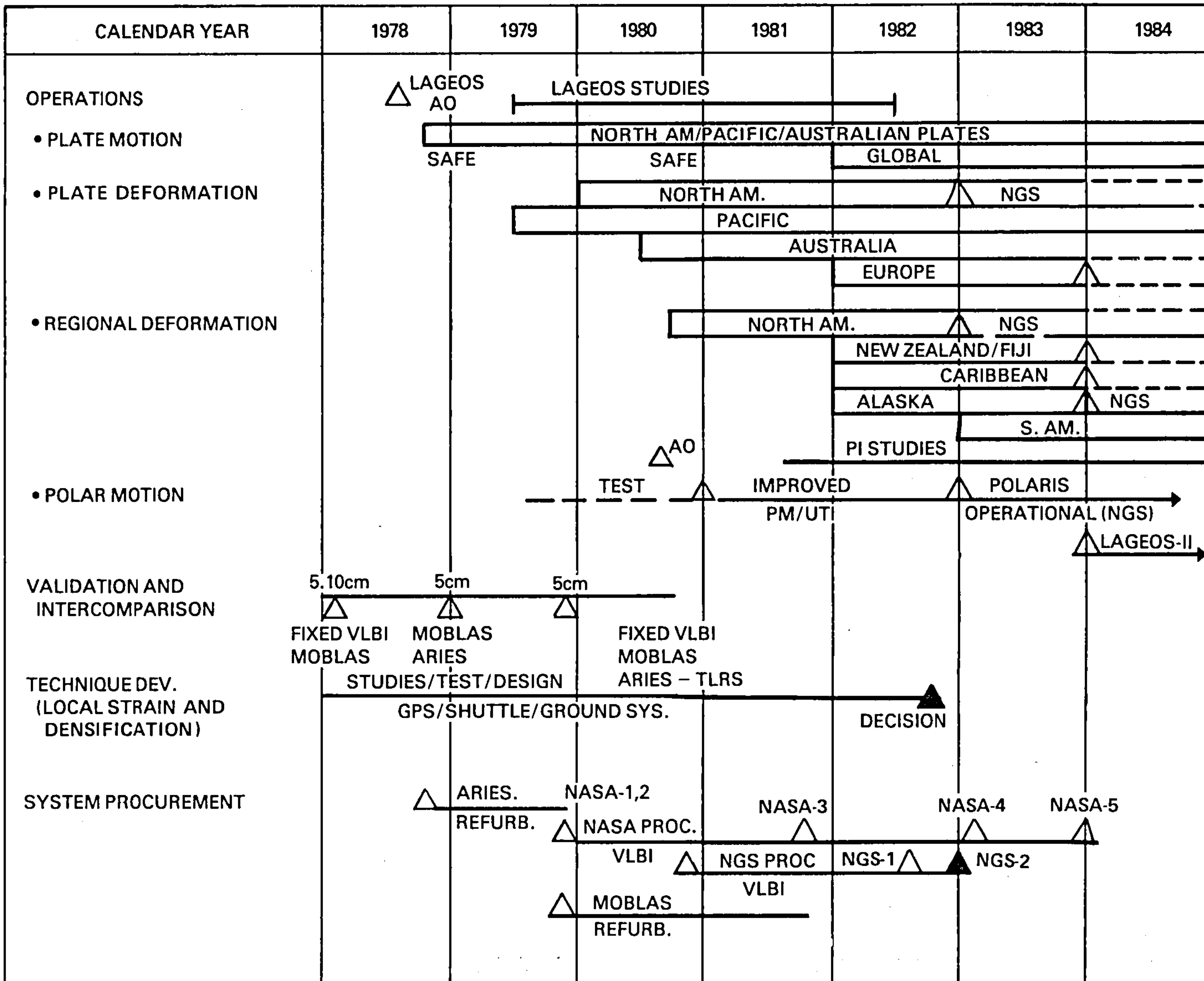


Figure 6.9-1. Crustal Dynamics Plan Overview.

6.9 IMPLEMENTATION SCHEDULE

The overall schedule for the plan described herein is summarized in Figure 6.9-1. Here we present in outline form the main activities by fiscal year.

6.9.1 Implementation Schedule

Phase 1 (FY 78-79):

a. Deployment of Moblas stations.

b. Initiation of Lageos investigations.

c. Initiation of North American, Pacific, and Australian plate motion and Pacific plate deformation studies.

d. Procurement of hardware for fixed VLBI observatories.

e. Completion of 4m VLBI station prototype.

f. Completion and testing of TLRS.

g. Routine operation of LURE Observatory (Haleakala) for satellite tracking.

h. Selection of sites and preparation for mobile station operation; logistics planning.

i. Continuation of studies for local strain measurement techniques.

Phase 2 (FY 80-81):

a. Initiation of Polaris network operation (two fixed VLBI observatories).

b. Development of global VLBI network of fixed antennas.

c. Establishment of data management and data processing systems.

d. Upgrading of 4m and 9m (ARIES) VLBI stations.

e. Beginning of Caribbean regional deformation studies.

f. Construction and delivery of new mobile VLBI station.

g. Initation of NGS procurement of two mobile VLBI stations.

h. Upgrading of Moblas stations.

i. Beginning of extended regional strain observations in Western North America and "benchmark" measurements at strategic locations around the world.

j. Continuation of systems development for laser ranging and VLBI.

k. Tests of GPS/VLBI technique for local strain measurement.

l. Beginning of data analysis and synthesis program (PI program).

<u>Phase 3 (FY 82-83)</u>:

a. Completion of Lageos investigation program.

b. Continuation of regional strain and plate deformation studies in North America, Australia, and the Pacific.

c. Delivery of NGS mobile VLBI stations.

d. Initiation of NGS operational responsibility for US plate and regional deformation studies.

e. Beginning of regional strain studies in New Zealand, South America, Alaska, Japan, and the Mexico-Central American region.

f. Operational monitoring of polar motion and UT1 using VLBI (NGS Polaris network).

h. Continuation of fixed observatory operations.

i. Expansion of data analysis and synthesis program.

<u>Phase 4 (FY 84-)</u>:

a. Transfer of responsibility for regional deformation studies in New Zealand, South America, the Caribbean, and Alaska.

b. Initiation of regional deformation studies in the Middle East and Far East.

c. Initiation of international agreements for regional studies in other tectonic areas.

d. Establishment of an international body for program coordination and data exchange.

6.10 PROGRAM COST ESTIMATES

We have developed estimates of the costs associated with accomplishment of the Crustal Dynamics Plan within the schedules and requirements established in previous sections. The estimated cost of the program through 1985 is provided in Table 6.10-1. Here we discuss the rationale for these estimates.

6.10.1 Fixed VLBI and Laser Facilities

Funding has been provided for operations of fixed VLBI stations in the US; for NASA support of the NGS Polaris Program; for the development of two portable VLBI data systems; and for the conversion of an existing antenna at Goldstone, California to a dedicated support facility for mobile VLBI measurements.

Operation of the laser facilities at the McDonald Observatory and Haleakala, Hawaii are continued. In FY 1979, the 30" Lageos/lunar stand-alone facility at McDonald (MLRS) will be initiated using hardware developed under the TLRS project and will replace the McDonald Observatory ranging in early 1981. Since this facility will also be capable of calculating the lunar ephemeris and of processing ranging data to satellites and the Moon, an appreciable cost savings will be realized.

Operation of Moblas stations at permanent locations at approximately $500K per year has been provided. In addition, it has been assumed that upgrading of Moblas to the 1-2 cm ranging capability will require $300K per station.

Although funding is provided for the next several years for continuation of the SAO station operations, it is assumed that the cost of these stations will be borne by the host countries starting in 1981.

6.10.2 Mobile VLBI and Laser Facilities

Upgrading of the existing 9m and 4m mobile VLBI units will require the procurement of Mark III data systems and rework of the mechanical and electrical systems. Procurement of a third unit through commercial sources is expected to cost $3.0M for the first system. Additional systems procurements for two more units have been estimated at $1.5M each.

To satisfy requirements for regional deformation studies through 1984 (210 site visits per year) two additional VLBI units ($1.5M each) and a TLRS unit ($750K) will be procured during FY 1981 to FY 1983.

6.10.3 Ground System Operations

Several factors must be considered in costing operations of ground systems. These include the cost of crews to operate the facilities; the cost of site preparations, and the cost of survey measurements needed to assure the stability of sites by isolating effects due to local changes unassociated with direct crustal deformation. Examples are the subsidence of areas due to water withdrawal, and post-glacial uplift. The extent of such surveys is difficult to estimate and will depend on experience and the local area. It would be reasonable however, to assume that a cost of $20K per site for at least the initial years would be needed. If it proves feasible to use the TLRS laser as a horizontal geodimeter, these costs for sites visited by the TLRS would be considerably less.

6.10.4 Data Management and Analysis

Data processing costs have been estimated on the basis of $20K per site visit (either laser ranging or VLBI).

The data analysis costs assume an investigator program expanding in FY 1982 to about 30 investigators at a cost of about $100K/year each.

6.10.5 Space Systems

The space systems considered include: Gravsat-A and -B, Magsat-B, the SGRS, and Lageos II. It is assumed that the Gravsat-A mission would consist of two low-altitude drag-free satellites launched by the Space Shuttle and tracked by either GPS or TDRSS systems. For Gravsat-B (1988), it is planned to fly a gravity gradiometer, and funding is provided for development of the instrument.

While funding is also included for a spaceborne laser on a dedicated long-lived spacecraft, it is realized that the GPS geodetic techniques may make such a mission unnecessary. However, it will be 1982 before sufficient test data on GPS concepts and cost effectiveness will be available to properly assess the need for SGRS.

In addition to the above, funding is provided for a second Lageos mission (Lageos II), and the follow-on to Magsat-A.

6.10.6 Advanced Techniques and System Development

In support of objectives for local strain measurements, development of the GPS interferometric technique was initiated in FY 1979 and is to be continued in FY 1980. The initial development will provide one set of receiver systems for intercomparison in late 1980 with an advanced GPS doppler system funded by DMA. Additional interferometric units will be procured in FY 1981 to support demonstration of the performance and cost effectiveness of the concept.

Funding is also provided (starting in FY 1981) for the development of advanced, highly compact, laser ranging systems.

TABLE 6.10-1

PROGRAM COST ESTIMATES (IN MILLIONS)

	1979	1980	1981	1982	1983	1984	1985
Fixed Laser & VLBI	9.0	10.1	11.7	14.2	10.4	9.5	9.8
Mobile Laser and VLBI	1.0	3.5	4.5	6.6	6.0	4.8	4.3
Ground Survey		0.5	0.8	1.2	1.5	1.5	1.5
Data Handling and Analysis	2.3	3.4	4.1	4.4	6.0	6.5	7.0
SUBTOTAL	12.3	17.5	21.1	26.4	23.9	22.3	22.6
Space Systems							
- Gravsat-A				8.0	25.0	15.0	6.0
- Gradiometer				1.0	3.0	5.0	2.0
- Magsat-B				10.0	12.0	3.0	2.0
- Lageos-II					3.0	5.0	3.0
- SGRS				1.0	8.0	15.0	2.0
SUBTOTAL				20.0	51.0	43.0	15.0
Advanced Technology & System Development		0.4	1.5	2.2	2.8	--	--

APPENDIX A

LUNAR LASER RANGING: HISTORY AND ACTIVITIES

Lunar laser ranging was conceived in the late 1950's when the gravitational research group at Princeton showed that precision tracking of a high-altitude satellite could be used to measure possible changes in the gravitational constant (Dicke et al., 1961). The usefulness of such a technique not only for relativity studies but also for lunar science, celestial mechanics, and lunar and terrestrial geodesy led NASA to include the Lunar Ranging Retroreflector Experiment in the Apollo Program and the Soviets to place two French retroreflectors on the Moon in their Luna program. The detailed history of these developments is given by Bender et al. (1973).

A.1 THE APOLLO LUNAR RANGING RETROREFLECTOR EXPERIMENT

The scientific objectives of this experiment, which was proposed in 1964 and begun in 1969, were:

1. To improve the determination of the lunar orbit.

2. To determine the locations of the reflectors with respect to the lunar center of mass, for use as a control net for lunar geodesy and cartography.

3. To study the physical librations of the Moon in order to determine the fractional lunar moments of inertia.

4. To determine the location of the ranging stations with respect to the center of mass of the earth.

5. To study gravitational theory by analysis of position deviations of the moon remaining after modeling known parameters.

Retroreflectors were placed on the Moon by the crews of Apollo 11, 14, and 15. Two other reflectors were emplaced by the Soviet Luna 17 and 21 missions. Ranging to all these reflectors began shortly after each of these missions, and is still continuing (except in the case of Luna 17, which was observed only twice soon after its landing; it is presumed that dust coverage or some accident on site was responsible for its loss). The arrangement of the four working reflectors on the Moon is a quadrilateral with sides of about 1000 kilometers, a good one for the study of lunar librations.

A.2 ACCOMPLISHMENTS

Although the great majority of lunar ranging observations to date have been made at only one observatory (McDonald Observatory, in Fort Davis, Texas), a remarkable number of accomplishments have been made by the lunar laser ranging program.

The laser ranging observations are two to three orders of magnitude more powerful than the previous optical methods for determining the position of the Moon, and corresponding improvements have been made in the lunar ephemeris. The lunar ranging data have been used to construct an ephemeris which gives the position of the Moon to within about 25 meters (Williams, 1977). This LURE-2 ephemeris models many effects which had not been previously incorporated into lunar theory, such as relativity, the lunar gravity field, and higher harmonics of the earth's gravity field.

Work is now in progress to include smaller effects such as solid-body tides on the Moon and the interaction between the earth's oblateness and the sun.

The position of the reflectors on the Moon is known in selenocentric coordinates to about 25 meters, and the relative position of the reflectors to about half this amount. These positions are key control points in the lunar cartographic system.

An important geophysical quantity is the secular acceleration of the longitude of the Moon caused by tidal dissipation in the earth, which controls slowing down the rotation of the earth. This quantity provides information on the phase of the major tidal components and put bounds on the bulk anelasticity of the earth at very long periods. Lunar laser ranging has given additional very precise determinations of this quantity: -24.6 ± 1.6 arc seconds per century (Calame and Mulholland, 1978) and -23.8 ± 4 (Williams et al., 1978). The Calame and Mulholland error figure is a formal statistical error, and the true error is likely to be several times higher. Further observations will result in significant refinement of the accuracy of this figure, and this alone provides strong justification for continuation of lunar laser ranging.

In relativity, lunar ranging does provide a method for estimating possible changes in the gravitational constant, as Dicke and his colleagues anticipated. Attempts to calculate this quantity from existing data have been inconclusive (Van Flandern, 1975; Reasenberg and Shapiro, 1976; Calame and Mulholland, 1978), and acquisition of further data will help to establish reasonable bounds on this important quantity. However, planetary orbiter and lander tracking will probably give more accurate results.

On the other hand, lunar laser ranging is the most accurate method at present to investigate other aspects of gravitation. Certain gravitational relativity theories predict a term in the motion of the Moon that exists neither in Newtonian mechanics or in Einstein's theory of general relativity. The term, called the Nordtvedt effect, arises from possible changes in the ratio of gravitational mass to inertial mass due to gravitational self energy. Lunar ranging results show that this term is zero to within quite small limits (Shapiro et al., 1976; Williams et al., 1976), which effectively eliminates certain theories from serious consideration in relativity theory.

Studies of lunar physical librations have yielded results of importance for lunar science. The fractional moment of inertia ratios β and γ have been determined to less than 0.3%, along with several higher harmonics of the lunar gravity field. Combining the moment of inertia ratios with values of the principal gravity field harmonic J_2 from tracking of lunar orbiting spacecraft has made it possible to calculate the normalized principal moment of inertia of the Moon as $C/MR^2 = 0.392 \pm 0.003$, which is a very important constraint on models of the distribution of mass in the lunar interior, particularly with respect to the question of the existence of a lunar core (Williams et al., 1973; Williams, 1977). Further observations will result in refinement of this determination.

Counselman and his colleagues at MIT have studied the relative position of the ALSEP transmitters at the Apollo landing sites using VLBI techniques (King et al., 1976). These observations have been incorporated into the geodetic control net for the Moon, along with the laser ranging data. It is also possible to use VLBI observations involving the ALSEP's and distant radio sources (quasars) to relate the position of the Moon to the celestial coordinate reference frame used by VLBI, and research is continuing on this problem (Slade et al., 1977).

Lunar laser ranging has also made important contributions to terrestrial geodesy and geophysics. The value, determined by this method, of the product of gravitational constant and the mass of the earth (GM), a fundamental quantity in geodesy, has been adopted as a standard by IUGG. Important studies of polar motion and earth rotation have been published by Stolz et al. (1976), Harris and Williams (1977), and King et al. (1978). The first measurement of an intercontinental baseline using lunar laser ranging was reported by Calame (1975).

A.3 ACTIVITIES

Lunar laser ranging operations at McDonald Observatory use the 107" telescope, the tenth largest astronomical telescope in the world. The present plan includes provision for constructing a separate 30" telescope facility at McDonald to replace the 107" operations, since technological advances no longer make it necessary to divert the large telescope for this purpose.

The LURE Observatory on Haleakala, Maui, is operated by the Institute for Astronomy of the University of Hawaii. It uses a 16" coelostat-configured telescope as a transmitter for pulses generated by a Nd:YAG Sylvania laser. Returns are received by the Lurescope, a novel type of telescope designed and constructed by James Faller of the University of Colorado and the National Bureau of Standards. The Lurescope contains an array of 80 8" lenses (the optical equivalent of an 80" conventional telescope) mounted in a small rigid structure that can be guided entirely by computer. The lenses feed into a single photomultiplier.

The first returns from the Moon were acquired by Haleakala in August, 1976, and the observatory has been carrying out a program of checkout and calibration since that time. Modifications are being made to allow the 16" telescope alone to range to artificial satellites.

Data from the laser ranging observatories are filtered and reduced by the Department of Astronomy of the University of Texas at Austin, and distributed to users through the National Space Science Data Center. The EROLD campaign previously described will eventually provide for international distribution of all lunar laser ranging data.

Lunar laser ranging stations are in various stages of development in several other countries. The Crimean Astrophysical Observatory has acquired data intermittently. Other stations are in various stages of construction at Orroral Valley (Australia), Dodaira (Japan), Grasse (France), and Wettzell (West Germany). All these are expected to participate in the exchange of data for study of polar motion and earth rotation via EROLD.

APPENDIX B

FIXED VLBI DEVELOPMENT

Since the initial VLBI geodetic measurements in 1969, there has been considerable development of the technology for high-accuracy geodetic applications. The key features of the VLBI system optimized for geodetic applications are as follows:

1. Very wide band receiver front end (400 MHz) for high-delay resolution.

2. Dual frequency (X-band and S-band) receiver system for extraction of the ionospheric delay.

3. Continuous system calibration.

4. Very stable hydrogen maser clock system.

5. Water vapor radiometer instruments and meteorological sensors for the determination of tropospheric propagation effects.

6. Very wide bandwidth (100 MHz) data system for obtaining a good signal-to-noise ratio when using small antennas.

7. Automated control and monitoring with a minicomputer in order to facilitate field operations.

The present status in the development of VLBI technology is reflected in the systems used for intercomparison of VLBI systems with satellite laser ranging systems in tests conducted in December 1977 through March 1978. The three intercomparison stations were Haystack Observatory in Westford, Massachusetts, the Owens Valley Radio Observatory in Bishop, California, and the DSN-14 station at Goldstone, California. The VLBI configuration used for this intercomparison had wide-band S/X receivers with calibration systems at Haystack and Owens Valley. The DSN-14 station used S-band and X-band but with a narrow-band (40 MHz) data system, with calibration. All three stations had stable hydrogen maser time standards. None of the stations used the Mark-III (4 MBs) systems. The three stations had local meteorological sensors but not water vapor radiometers.

There has been more than one year's operational experience with this type of station configuration. Short baseline tests by the Goddard-Haystack-MIT group have demonstrated equipment accuracy and stability at the 5 millimeter level. They have made repeated measurements of the Haystack-OVRO baseline with a precision of better than 2 centimeters (Rogers et al., 1978). The JPL ARIES team has measured the baseline between their transportable 9-meter antenna and the OVRO and Goldstone stations, and compared their results with high-accuracy surveys by the National Geodetic Survey. These measurements demonstrated an accuracy of better than 10 centimeters for baselines up to 400 kilometers in length.

Although water vapor radiometers have not been used extensively in operations, considerable testing of the technology has been done both by JPL and the East Coast groups. JPL has demonstrated agreement at approximately the 1.5 centimeter level between water vapor radiometer measurements of atmospheric water vapor and measurements by radiosondes, instrumented aircraft, and solar hydrometers. Similarly, the Haystack measurements have demonstrated agreement at about the 2 centimeter level between water vapor radiometry measurements of atmospheric water vapor and measurements by radiosondes. As a consequence of these successful tests, both Goddard and JPL are proceeding with the implementation of operational water vapor radiometer systems.

The Mark III wideband data system has been under development by a group from Goddard, Haystack, MIT, and the National Radio Astronomy Observatory. In September 1977 the breadboard test of the new Mark III system was conducted with systems at the Haystack Observatory and NRAO. In this test, six channels of 4 MHz each were used for recording the VLBI data. These six data channels were multiply recorded on the 28 tracks of the high data rate recorder. This permitted operational testing of all elements of the system. This test was successful. Implementation of the full system has been completed at Haystack, NRAO, and OVRO. Tests are expected in mid-1979 with the goal of demonstrating a 5 cm capability.

Preliminary work has started on the implementation of a Mark III capability at Ft. Davis, Texas. The Ft. Davis station will be one element of the NGS Polaris system for polar motion monitoring, anticipated to be operational by 1983 using antennas at Ft. Davis, Richmond (Florida) and Westford (Massachusetts).

The NASA Deep Space Network uses the VLBI technique operationally for tracking spacecraft on interplanetary and other deep space missions. Presently, this system is working to a specification which would allow it to make intercontinental measurements at the 50 cm level. The system is capable of extension to perform baseline and polar motion measurements with accuracies required by the geodynamics program. As has been demonstrated by tests involving the DSN antenna at Goldstone and the mobile ARIES antenna, VLBI facilities at other worldwide DSN sites could be scheduled (on a time-sharing basis) to work with mobile VLBI stations in the global crustal dynamics program.

APPENDIX C

TECHNIQUE VALIDATION AND INTERCOMPARISON EXPERIMENTS

The laser ranging and VLBI techniques are inherently more accurate for long baseline measurements than conventional geodetic techniques over distances more than a few tens of kilometers. In order to validate these new approaches, to identify systematic errors, and to assess their absolute accuracy, experimental intercomparison measurements have been conducted over the past several years and more are planned for the period 1979-80.

In 1974, a short (307 meters) baseline was measured between the prototype transportable 9-meter antenna developed by JPL and the 64-meter DSS-14 tracking antenna at Goldstone, California. The purpose of this short baseline measurement was to isolate the inherent VLBI instrumentation errors from those errors that are distance-related, such as atmospheric and ionospheric effects and source position errors. This measurement, made with an early version of the VLBI receiver and data correlator, showed an rms precision of ±3 cm and also agreed to within 3 cm with the local first-order survey made by conventional measurements.

Starting in early 1975, through May 1977, a series of short baseline measurements were made between the two radio astronomy antennas located 1.2 km apart at the Haystack and Westford Observatories just north of Boston (Rogers et al., 1978). The standard error of the mean baseline measurement was 3.1 cm, and this mean value agreed with the precise conventional geodetic survey between the two antennas to better than 5 mm. These measurements were made with a calibrated system using a Mark III correlator.

In early 1977, the transportable ARIES VLBI system, using Mark II technology, was operated with the Owens Valley Radio Observatory in northern California to measure an intermediate-length baseline of 41.5 km length across Santa Monica Bay. The transportable 9-meter antenna was positioned at Palos Verdes and then at Malibu, and measured the baseline (approximately 400 km) between each of these places and OVRO. The computed differential vector across the bay agreed with the direct line-of-sight laser geodimeter distance measurement and with the astrogeodetic-referenced direction measurement to within ±6 cm and 0.5 arc-seconds respectively.

The validation of mobile satellite laser ranging facilities (Moblas) is accomplished routinely by simultaneous ranging observations from co-located Moblas units at the fixed laser facility at GSFC (Stalas). While primarily a test of Moblas readiness, these observations assure the consistency of satellite laser ranging.

In late 1977 the first phase of an intensified laser/VLBI intercomparison was initiated. Upgraded Moblas units were deployed to the fixed VLBI sites at Haystack, OVRO, and Goldstone. The intent of these tests was to demonstrate the capability of these systems to measure continental baselines at the 10-50 cm level. In addition, the National Geodetic Survey located geoceivers at these and five other sites in the United States and abroad. Data were also acquired with the transportable ARIES VLBI unit at San Diego and at San Francisco, to compare the baseline vector between OVRO and Goldstone with that acquired by the laser and fixed VLBI systems. The San Diego to San Francisco vector was also computed in order to attempt to resolve a discrepancy between oceanographic and conventional geodetic estimates of the relative heights of tide gauges at these places.

The second and final phase of the intercomparison testing is planned for late 1979, with the goal of demonstrating an absolute accuracy of 5 cm over continental distances. A geometrically improved figure will be achieved using Ft. Davis, Texas. For these tests, five VLBI sites will be equipped with Mark III wide-band recording systems (or equivalent). The Moblas units will be capable of ranging to Lageos to ±10 cm or better. The Transportable Laser Ranging Station will be co-located at Ft. Davis. This will afford the first opportunity to intercompare Lageos ranging data from the Moblas systems with the single-photon system used by TLRS. Prior to these tests, TLRS data acquired sequentially over a gridded area in Texas will be compared with existing or new first-order position determinations by NGS.

Analysis of the validation and intercomparison observations (to be completed in mid-1981) will provide the accuracy verification needed to confirm the capability of these systems.

APPENDIX D

ABBREVIATIONS

ADS	Applications Data System
AFB	Air Force Base
ALSEP	Apollo Lunar Surface Experiment Package
ARIES	Astronomical Radio Interferometry for Earth Surveying
ARPA	Advanced Research Projects Agency
ASTP	Apollo-Soyuz Test Project
ATS	Applications Technology Satellite
BE	Beacon Explorer
BIH	Bureau International de l'Heure
CIT	California Institute of Technology
DARPA	Defense Advanced Research Projects Agency
DCP	Data Collection Platform
DSIR	Department of Scientific and Industrial Research (New Zealand)
DSN	Deep Space Network
EODAP	Earth and Ocean Dynamics Applications Program
EOPAP	Earth and Ocean Physics Applications Program
EROLD	Earth Rotation from Lunar Distances
ESA	European Space Agency
FY	Fiscal Year
GEOS	Geodynamics Experimental Ocean Satellite
GOES	Geostationary Operational Environmental Satellite
GSFC	Goddard Space Flight Center

GST	Goldstone, California, Deep Space Network Station
ICCG	Interagency Coordinating Committee for the Application of Space Technology to Geodynamics
ICG	Interunion Commission on Geodynamics
IDA	International Deployment of Accelerometers
IPMS	International Polar Motion Service
IR	Infrared
JPL	Jet Propulsion Laboratory
Lageos	Laser Geodynamic Satellite
LDGO	Lamont-Doherty Geological Observatory of Columbia University
LLR	Lunar Laser Ranging
LURE	Lunar Ranging Experiment
MLRS	McDonald Laser Ranging System
NAS	National Academy of Sciences
NASA	National Aeronautics and Space Administration
NGSP	National Geodetic Satellite Program
NOAA	National Oceanic and Atmospheric Administration
NRAO	National Radio Astronomy Observatory, Greenbank, West Virginia
NRC	National Research Council
NSF	National Science Foundation
OSTP	Office of Science and Technology Policy
OVRO	Owens Valley Radio Observatory, Bishop, California
PI	Principal Investigator
PM/ER	Polar Motion/Earth Rotation

Polaris	Polar Motion Analysis by Radio Interferometric Systems
PPME	Pacific Plate Motion Experiment
Ramlas	Range Measurement by Laser System (at Patrick AFB, Florida)
RANN	Research Applied to National Needs
RBV	Red-Blue-Violet
RRL	Radio Research Laboratories (Japan)
SAFE	San Andreas Fault Experiment
SAO	Smithsonian Astrophysical Observatory
SERIES	Satellite Emission Radio Interferometric Earth Surveying
SGRS	Shuttle Geodynamics Ranging Ssytem
SRO	Seismic Research Observatory
SST	Satellite-to-Satellite Tracking
Stalas	Stationary Laser Facility (at GSFC)
TDRSS	Tracking and Data Relay Satellite System
TLRS	Transportable Laser Ranging Station
TPM	Tectonic Plate Motion Project
USB	Unified S-Band
USGS	US Geological Survey
USNO	US Naval Observatory
UT	Universal Time
VLBI	Very Long Baseline Interferometry
WWSSN	Worldwide Standardized Seismograph Network

REFERENCES

Adams, R. P., Earthquake prediction: Nature 269, 14, 1977.

Aggarwal, Y. P., L. R. Sykes, J. Armbruster, and M. L. Sbar, Premonitory changes in seismic velocities and prediction of earthquakes: Nature 241, 101-104, 1973.

Allenby, R. J., W. J. Webster, and J. E. Painter, Satellite Relaying of Geophysical Data: NASA Report X-922-77-273, Goddard Space Flight Center, Greenbelt, Md., 1977.

Anderle, R. J., Transformation of terrestrial survey datum to doppler satellite datum: J. Geophy. Res. 79, 5319-5331, 1974.

Anderle, R. J., Application of Global Positioning System to determination of tectonic plate movements and crustal deformations: Proceedings of the Ninth Geodesy, Solid Earth, and Ocean Physics Conference, Ohio State University, Columbus, Ohio, October 1978.

Anderson, D. L., Earthquakes and the rotation of the earth: Science 186, 49-50, 1974.

Anderson, D. L., Frontiers of Geophysics: Earthquakes, volcanoes, climate, and the rotation of the earth (abstract): EOS, Trans. Amer. Geophys. Union 56, 346, 1975a.

Anderson, D. L., Accelerated plate tectonics: Science 187, 1077-1079, 1975b.

Atwater, T., Implications of plate tectonics for the Cenozoic evolution of western North America: Bull. Geol. Soc. Amer. 81, 3513-3536, 1970.

Barazangi, M., and H. J. Dorman, World seismicity map of ESSA Coast and Geodetic Survey epicenter data for 1961-1967: Bull. Seism. Soc. Amer. 369, 1969.

Beloussov, V. V., Why do I not accept plate tectonics?: EOS, Trans. Amer. Geophys. Union 60, 207-211, 1979.

Bender, P. L., J. E. Faller, J. Levine, S. Moody, M. R. Pearlman, and E. C. Silverberg, Possible high-mobility Lageos ranging station: Tectonophysics 52, 69-73, 1979.

Bender, P. L., and twelve others, The lunar laser ranging experiment: Science 182, 229-238, 1973.

Berberian, M., A brief geological description of North-Central Iran, in Materials for the Study of the Seismotectonics of Iran; North-Central Iran: Geol. Survey of Iran Report 29, 127-138, 1974.

Bowin, C., Caribbean gravity field and plate tectonics: Geol. Soc. Amer. Spec. Paper 169, 1976.

Brown, L. D., R. E. Reilinger, S. R. Holdahl, and E. I. Balazs, Postseismic crustal uplift near Anchorage, Alaska: J. Geophys. Res. 82, 3369-3378, 1977.

Burford, R. O., and T. W. Harsh, Slip on the San Andreas Fault in central California from alignment array surveys: Bull. Seism. Soc. Amer. (submitted, 1979).

Calame, O., Geodésie - premiere détérmination d'une longue base terrestre la télémetrie laser-lune et localisation du réflecteur de lunakhud: Compt. Rend. Acad. Sci. Paris 280, 551, 1975.

Calame, O., and J. D. Mulholland, Lunar tidal acceleration determined from laser range measures: Science 189, 977-978, 1978.

California Division of Mines and Geology, Guidelines for the evaluation of surface fault rupture: California Geology 29, 105-108, 1976.

Canby, T. Y., Can we predict quakes?: National Geographic 149, 830-835, 1976.

Carter, W. E., Modern methods for the determination of polar motion and UT1, Tenth Annual Precise Time and Time Interval Applications and Planning Meeting, Washington, D.C., November 1978.

Carter, W. E., and W. E. Strange, The National Geodetic Survey Project "Polaris:" Tectonophysics 52, 39-46, 1979.

Carter, W. E., and T. Vincenty, Survey of the McDonald Observatory Radial Line Scheme by Relative Lateration Techniques: Technical Report NOS-74-NGS-9, National Geodetic Survey, National Oceanic and Atmospheric Administration, Rockville, Maryland, 1978.

Castle, R. O., J. N. Alt, J. C. Savage, and E. I. Balazs, Elevation changes preceding the San Fernando Earthquake of February 9, 1971: Geology 2, 61-66, 1974.

Cohen, S. C., and G. R. Cook, Determining crustal strain rates with a spaceborne geodynamics ranging system; 1, Baseline analysis, NASA Report TM-79565, Goddard Space Flight Center, Greenbelt, Md., 1978.

Counselman, C. C., and I. I. Shapiro, Miniature Interferometer Terminals for Earth Surveying: Ninth Geodesy, Solid Earth, and Ocean Physics Conference, Ohio State University, Columbus, Ohio, October 1978.

Darwin, C., The Voyage of the Beagle: Doubleday & Co., New York, 1962.

Dewey, J. F., and J. M. Bird, Mountain belts and the new global tectonics: J. Geophys. Res. 75, 2625-2647, 1970.

Dewey, J. F., Suture Zone Complexities: Tectonophysics 40, 53-67, 1977.

Dicke, R. H., W. F. Hoffman, and R. Krotkov: Space Res. 2, 287, 1961.

Dickinson, W. R., and W. S. Snyder, Geometry of triple junctions related to San Andreas Transform: J. Geophys. Res. 84, 561-572, 1979.

Drake, C. L. (editor), Geodynamics: Progress and Problems: American Geophysical Union, Washington, DC, 1976.

Engdahl, E. R., Seismicity and plate subduction in the Central Aleutians, in Island Arcs, Deep-Sea Trenches, and Back-Arc Basins, ed. M. Talwani and W. Pitman: Amer. Geophys. Union, Washington, D.C., 1977.

Engdahl, E. R., N. H. Sleep, and M. T. Lin, Plate effects in North Pacific subduction zones: Tectonophysics 37, 95-116, 1977.

European Space Agency, Proceedings of the European Workshop on Space Oceanography, Navigation, and Geodynamics, held at Schloss Elmau, West Germany, January 16-21, 1978.

European Space Agency, Proposal for a European programme of earthquake prediction research: Proceedings of the Seminar on Earthquake Prediction Research, European Space Agency Report SP-149, April 1979.

Felsentreger, T. L., J. G. Marsh, and R. W. Agreen, Analysis of the solid earth and ocean tidal perturbations on the orbits of the GEOS-1 and GEOS-2 satellites: J. Geophys. Res. 81, 2557-2563, 1976.

Gaposchkin, E. M., Earth's gravity field to the eighteenth degree and geocentric coordinates for 104 stations from satellite and terrestrial data: J. Geophys. Res. 79, 5377-5411, 1974.

Gergen, J., Horizontal displacements in the earth's crust in the vicinity of El Centro, California (abstract): EOS, Trans. Amer. Geophys. Union 59, 242, 1978.

Goad, C. C., and B. C. Douglas, Lunar longitude deceleration and tidal parameters estimated from satellite orbital perturbations, Eighth International Symposium on Earth Tides, Bonn, West Germany, 1977.

Hamilton, W., Mesozoic tectonics of the Western United States, in Mesozoic Paleogeography in the Western United States, Soc. Econ. Paleontologists and Mineralogists, Boulder, Colorado, 1978.

Harper, J. F., Subduction-zone vortices: Bull. Austr. Soc. Explor. Geophys. 6, 79-80, 1975.

Harris, A. W., and J. G. Williams, Earth Rotation Study Using Lunar Laser Ranging, in Scientific Applications of Lunar Laser Ranging, ed. J. D. Mulholland: D. Reidel, Dordrecht, 1977.

Haxby, W. F., and D. L. Turcotte, On isostatic geoid anomalies: J. Geophys. Res. 83, 5473-5478, 1978.

Henriksen, S. W., ed., National Geodetic Satellite Program Final Report: NASA Rept. SP-365, Washington, D..C., 1977.

Henriksen, S. W., and I. I. Mueller, Major results of the National Geodetic Satellite Program: J. Geophys. Res. 79, 5317-5318, 1974.

Hill, M. L., and T. W. Dibblee, San Andreas, Garlock, and Big Pine faults, California: Bull. Geol. Soc. Amer. 64, 443-458, 1953.

Huggett, G. R., L. E. Slater, and G. Paulis, Precision leveling with a two-fluid tiltmeter: Geophys. Res. Lett. 3, 754-756, 1976.

Jeffreys, H., Causes cóntributory to the annual variation of latitude: Mon. Not. Roy. Astron. Soc. 26, 499, 1916.

Johnson, C., Swarm tectonics of the Imperial and Brawley faults of Southern California (abstract): EOS, Trans. Amer. Geophys. Union 58, 1188, 1977.

Johnston, M. L. S., and C. E. Mortensen, Tilt precursors before earthquakes on the San Andreas fault, California: Science 186, 1031-1034, 1974.

Jordan, T. H., The present-day motions of the Caribbean plate: J. Geophys. Res. 80, 4433-4439, 1975.

Journal of Geophysical Research, Special Issue on Scientific Results of the GEOS-3 Mission: volume 84 (in press), 1979.

Journal of Geophysical Research, Special Issue on Earthquake Fault Mechanism: vol. 84, no. 85, 2145-2370, 1979.

Kagan, Y., and L. Knopoff, Statistical search for non-random features in the seismicity of strong earthquakes: Phys. Earth Planet. Interiors 12, 291-318, 1976.

Kanamori, H., Seismic and aseismic slip along subduction zones and their tectonic implications, in Island Arcs, Deep-Sea Trenches, and Back-Arc Basins, ed. M. Talwani and W. C. Pitman, III: Am. Geophys. Union, Washington, D. C., 1977a.

Kanamori, H., The energy release in great earthquakes: J. Geophys. Res. 82, 2981-2987, 1977b.

Kanamori, H., and J. J. Cipar, Focal process of the great Chilean earthquake of May 22, 1960: Phys. Earth Planet. Interiors 9, 128-136, 1974.

Kanamori, H., and Anderson, D. L., Theoretical basis of some empirical relations in seismology: Bull. Seis. Soc. Amer. 65, 1073-1095, 1975.

Kaula, W. M., A tectonic classification of the main features of the earth's gravitational field: J. Geophys. Res. 74, 4807-4826, 1969.

King, R. W., C. C. Counselman, III, and I. I. Shapiro, Lunar dynamics and selenodesy: results from analysis of VLBI and laser data: J. Geophys. Res. 81, 6251-6256, 1976.

King, R. W., C. C. Counselman, III, and I. I. Shapiro, Universal Time: Results from lunar laser ranging: J. Geophys. Res. 83, 3377-3381, 1978.

Kovalevsky, J., P. Melchior, R. Sigal, and G. Veis, Report of the Steering Committee, in Proceedings of the European Workshop on Space Oceanography, Navigation, and Geodynamics, European Space Agency, 1978.

Lambeck, K., and Cazenave, A., Long-term variations in the length of day and climate change: Geophys. J. Roy. Astron. Soc. 46, 555-574, 1976.

Lambeck, K., Cazenave, A., and G. Balmino, Solid earth and ocean tides estimated from satellite orbit analysis: Revs. Geophys. Space Phys. 12, 421-434, 1974.

Lambeck, K., Progress in geophysical aspects of the rotation of the earth: Proceedings of the Ninth Geodesy, Solid Earth, and Ocean Physics Conference, Ohio State University, Columbus, Ohio, October 1978.

Lathram, E., Nimbus IV view of the major structural features of Alaska: Science 175, 1423-1427, 1972.

Lerch, F. J., S. M. Klasko, R. E. Laubscher, and C. A. Wagner, Gravity model improvement using GEOS-3 (Gem 9 and 10): Rept. X-921-77-246, Goddard Space Flight Center. Greenbelt, Md., 1977.

Levine, J., Multiple wavelength geodesy: Proceedings of the Ninth Geodesy, Solid Earth, and Ocean Physics Conference, Ohio State University, Columbus, Ohio, October, 1978.

Lonsdale, P., and K. D. Klitgord, Structure and tectonic history of the eastern Panama Basin: Geol. Soc. Amer. Bull. 89, 981-999, 1978.

Lowman, P. D., Geological structure in California; three studies with ERTS-1 imagery: NASA Rept. X-922-77-314, Goddard Space Flight Center, Greenbelt, Md., 1974.

Lowman, P. D., Jr., and H. V. Frey, eds., A Geophysical Atlas for Interpretation of Satellite-Derived Data: NASA Report TM79722, Goddard Space Flight Center, Greenbelt, Md., 1979.

MacDoran, P. F., A. E. Niell, K. M. Ong, G. M. Resch, D. D. Morabito, E. S. Claflin, and T. G. Lockhart, Mobile radio interferometric geodetic systems: Proceedings of the Ninth Geodesy, Solid Earth, and Ocean Physics Conference, Ohio State University, Columbus, Ohio, October 1978.

MacDoran, P. F., SERIES GPS geodetic system: Bull. Geodesique (submitted, 1979).

Mansinha, L., and D. E. Smylie, Effects of earthquakes on the Chandler wobble and the secular pole shift: J. Geophys. Res. 72, 4731-4743, 1967.

McNally, K. C., E. Chael, and L. Ponce, The Oaxaca, Mexico, earthquake (M_s = 7.8) of 29 November 1978: New "pre-failure" observations (abstract): EOS, Trans. Amer. Geophys. Union, 1979.

Melosh, H. J., and A. Raefsky, Surface deformation due to vertical dip-slip faulting in a non-Newtonian earth (abstract): EOS, Trans. Amer. Geophys. Union, 1979.

Minster, J. B., T. H. Jordan, P. Molnar, and E. Haines, Numerical modelling of instantaneous plate tectonics: Geophys. J. Roy. Astron. Soc. 36, 541-576, 1974.

Minster, J. B., and T. H. Jordan, Present-day plate motions: J. Geophys. Res. 83, 5331-5354, 1978.

Minster, J. B., and T. H. Jordan, Present-day plate motions; A summary: Phys. Earth Planet. Interiors (in press), 1979.

Molnar, P., and Tapponier, P., Relations of the tectonics of eastern China to the India-Eurasia collision: application of slip-line field theory to large-scale continental tectonics: Geology 5, 212-216, 1977.

Molnar, P., and P. Tapponier, Active Tectonics of Tibet: J. Geophy. Res. 83, 5361-5376, 1978.

Muehlberger, W. R., and Ritchie, A. W., Caribbean-Americas plate boundary in Guatemala and Southern Mexico as seen on Skylab IV orbital photography: Geology 3, 232-235, 1975.

Mueller, I. I., Global satellite triangulation and trilateration results: J. Geophys. Res. 79, 5333-5347, 1974.

Mueller, I. I. (ed.), Applications of Geodesy to Geodynamics: Proceedings of the Ninth Geodesy, Solid Earth, and Ocean Physics Research Conference, October 2-5, 1978 (Ohio State University, Department of Geodetic Science Report No. 280), 1978.

Munk, W., and G. J. F. MacDonald: The Rotation of the Earth, Cambridge University Press, Cambridge, 1960.

Nason, R. D., Investigation of fault creep slippage in Northern and Central California: Ph.D. thesis, University of California at San Diego, 1971 (University Microfilms #72-12785, Ann Arbor, Michigan).

Nason, R. D., Measurements and theory of fault creep slippage in Central California: in Proceedings of a Symposium on Recent Crustal Movements, Roy. Soc. New Zealand Bull. 9, 181-187, 1971.

National Academy of Sciences: Geodesy: Trends and Prospects, Washington, D. C., 1978.

National Academy of Sciences: U.S. Program for the Geodynamics Project, Washington, D. C., 1973.

National Academy of Sciences, Predicting Earthquakes, Washington, D.C., 1976.

National Academy of Sciences, Crustal Dynamics: A Framework for Resource Systems, Washington, D.C., in press, 1979.

National Aeronautics and Space Administration, The Terrestrial Environment: Solid Earth and Ocean Physics, Applications of Space and Astronomical Techniques, Washington D.C., 1969.

National Aeronautics and Space Administration, NASA Plan for International Crustal Dynamics Studies: NASA Headquarters, Washington, DC, April 1979.

National Aeronautics and Space Administration, National Oceanic and Atmospheric Administration, US Geological Survey, National Science Foundation, and Defense Mapping Agency, The Coordinated Federal Program for the Application of Space Technology to Crustal Dynamics and Earthquake Research, Washington, DC, 1979.

Ni, J., and J. E. York, Late Cenozoic tectonics of the Tibetan Plateau: J. Geophys. Res. 83, 5377-5384, 1978.

Nur, A., and Z. Ben-Avraham, Continental fragments and collisions in the circum-Pacific belt (abstract): EOS, Trans. Amer. Geophys, Union 58, 1231, 1977.

Office of Science and Technology Policy, Earthquake prediction and hazard mitigation: Options for USGS and NSF Program, Washington, D. C., Sept., 1976.

Ohtake, M., T. Matumoto, and G. V. Latham, Seismicity gap near Oaxaca, Southern Mexico, as a probable precursor to a large earthquake: Pageoph 115, 375-385, 1977.

Okal, E. A., The July 9 and 23, 1905, Mongolian earthquakes: a surface wave investigation: Earth Planet. Sci. Lett. 34, 326-331, 1977.

Ong, K. M., P. F. MacDoran, A. E. Niell, G. N. Resch, D. D. Morabito, and T. G. Lockhart, Radio interferometric geodetic monitoring in Southern California (abstract): EOS, Trans. Amer. Geophys. Union 58, 1121, 1977.

Plafker, G., Tectonics of the March 27, 1964, Alaska earthquake: US Geol. Surv. Prof. Paper 543-I, 1-74, 1969.

Press, F., Earthquake prediction: Scientific American 232, 14-23, 1975.

Press, F., and P. Briggs, Chandler wobble, earthquakes, rotation, and geomagnetic changes: Nature 256, 270-273, 1975.

Raleigh, C. B., G. Bennett, H. Craig, T. Hanks, P. Molnar, A. Nur, J. Savage, C. Scholz, R. Turner, and F. Wu, Prediction of the Haicheng earthquake (abstract): EOS, Trans. Amer. Geophys. Union 58, 236-272, 1977.

Reasenberg, R. D., and I. I. Shapiro, in Atomic Masses and Fundamental Constants, Vol. 5, ed. J. H. Saunders and A. H. Wapstra, Plenum Press, New York, 1976.

Reilinger, R. E., G. P. Citron, and L. D. Brown, Recent vertical crustal movements from precise leveling data in southwestern Montana, Western Yellowstone National Park, and the Snake River Plain: J. Geophys. Res. 82, 5349-5359, 1977.

Reilinger, R. E., G. Jurkowski, L. D. Brown, and J. E. Oliver, Interpretation of vertical crustal movements as indicated by leveling in intraplate areas: Proceedings of the Ninth Geodesy, Solid Earth, and Ocean Physics Conference, Ohio State University, Columbus, Ohio, October 1978.

Rial, J. A., The Caracas, Venezuela, earthquake of July 1967: a multiple-source event: J. Geophys. Res. 83, 5405-5414, 1978.

Richter, F., and S. F. Daby, Convection models having a multiplicity of large horizontal scales: J. Geophys. Res. 83, 4951-4956, 1978.

Rikitake, T., An approach to prediction of magnitude and occurrence time of earthquakes: Tectonophysics 8, 81-95, 1969.

Rikitake, T., Earthquake Prediction: Elsevier, The Hague, Netherlands, 1976.

Robertson, D. S., Geodetic and astrometric measurements with very-long-baseline interferometry: NASA Rept. X922-77-228, Goddard Space Flight Center, Greenbelt, Md., 1975.

Robertson, D. S., W. E. Carter, B. E. Corey, C. C. Counselman, I. I. Shapiro, J. J. Wittels, H. F. Hinteregger, C. A. Knight, A. E. E. Rogers, J. W. Ryan, T. A. Clark, R. J. Coates, C. Ma, and J. M. Moran, Recent results of radio interferometric determinations of polar motion and earth rotation: Proceedings IAU Symposium No. 82, in press, 1979.

Rogers, A. E. E., C. A. Knight, H. F. Hinterreger, A. R. Whitney, C. C. Counselman, I. I. Shapiro, S. A. Gourevitch, and T. A. Clark, Geodesy by radio interferometry: determination of a 1.24 km base line vector with 5mm repeatability: J. Geophys. Res. 83, 325-334, 1978.

Sabins, F. F., Remote Sensing; Principles and Interpretation: W. H. Freeman, San Francisco, 1978.

Savage, J. C., and R. O. Burford, Geodetic determination of relative plate motion in Central California: J. Geophys. Res. 78, 832-845, 1973.

Savage, J. C., and W. P. Prescott, Geodimeter measurements on the Palmdale Bulge, 1959-1977 (abstract): EOS, Trans. Amer. Geophys. Union 58, 1121, 1977.

Savage, J. C., and W. H. Prescott: Asthenospheric readjustment and the earthquake cycle: J. Geophys. Res. 83, 3369-3376, 1978.

Savage, J. C., Strain patterns and strain accumulation along plate margins: Proceedings of the Ninth Geodesy, Solid Earth, and Ocean Physics Conference, Ohio State University, Columbus, Ohio, October, 1978.

Savage, J. C., and W. H. Prescott: Geodimeter measurement of strain during the Southern California uplift: J. Geophys. Res. 84, 171-177, 1979.

Sbar, M. L., and L. R. Sykes, Contemporary compressive stress and seismicity in eastern North America: an example of intra-plate tectonics: Bull. Geol. Soc. Amer. 84, 1861-1882, 1973.

Schmid, H. H., Worldwide geometric satellite triangulation: J. Geophys. Res. 79, 5349-5371, 1974.

Scholz, C. H., L. R. Sykes, and Y. P. Aggarwal, Earthquake prediction: a physical basis: Science 181, 803-810, 1973.

Semenov, A. M., Variations in travel time of transverse and longitudinal waves before violent earthquakes: Izv. Acad. Sci. USSR, Phys. Solid Earth, 245-248, 1969.

Sengör, A. M. C., and K. Burke, Comments on "Why do I not accept plate tectonics?," by V. V. Beloussov: EOS, Trans. Amer. Geophys. Union 60, 207-211, 1979.

Sieh, K., Prehistoric large earthquakes produced by slip on the San Andreas Fault at Pallett Creek, California: J. Geophys. Res. 83, 3907-3939, 1978.

Shapiro, I. I., C. C. Counselman, and R. W. King, Verification of the principal of equivalence for massive bodies: Phys. Rev. Lett. 36, 555-558, 1976.

Shapiro, I. I., Principles of very-long-baseline interferometry: Proceedings of the Ninth Geodesy, Solid Earth, and Ocean Physics Conference, Ohio State University, Columbus, Ohio, October, 1978.

Silverberg, E. C., Mobile satellite ranging: Proceedings of the Ninth Geodesy, Solid Earth, and Ocean Physics Conference, Ohio State University, Columbus, Ohio, October 1978.

Singh, S. K., J. Havskov, K. McNally, L. Ponce, T. Hearn, and M. Vassilious, The Oaxaca, Mexico, earthquake of 29 November 1978: A preliminary report on aftershocks: Science (in press), 1979.

Slade, M. A., R. A. Preston, A. W. Harris, L. J. Skjerve, and D. J. Spitzmesser, ALSEP-Quasar Differential VLBI: The Moon 17, 133-147, 1977.

Smith, D. E., R. Kolenkiewicz, P. J. Dunn, and M. Torrence, The measurement of fault motion by satellite laser ranging: Tectonophysics (in press), 1979.

Smith, D. E., F. J. Lerch, J. G. Marsh, C. A. Wagner, R. Kolenkiewicz, and M. A. Khan, Contributions to the National Geodetic Satellite Program by the Goddard Space Flight Center: J. Geophys. Res. 81, 1006-1026, 1976.

Smith, D. E., R. Kolenkiewicz, and P. J. Dunn, Determination of the earth tidal amplitude and phase from orbital perturbations of the Beacon Explorer C spacecraft: Nature 244, 498, 1973.

Smith, D. E., Spaceborne ranging systems: Proceedings of the Ninth Geodesy, Solid Earth, and Ocean Physics Conference, Ohio State University, Columbus, Ohio, October, 1978.

Smith, D. E., and B. D. Tapley (editors), Report from the Workshop on the Spaceborne Geodynamics Ranging System: Report TR79-2, Institute for Advanced Study in Orbital Mechanics, University of Texas, Austin, Texas, 1979.

Smith, M. L., Wobble and nutation of the Earth: Geophys. J. Roy. Astron. Soc. 50, 103-140, 1977.

Smylie, D. E., and L. Mansinha, Earthquakes and the observed motion of the rotation pole: J. Geophys. Res. 73, 7661-7673, 1968.

Snay, R. A., and J. G. Gergen, Monitoring regional crustal deformation with horizontal geodetic data: Proceedings of the Ninth Geodesy, Solid Earth, and Ocean Physics Conference, Ohio State University, Columbus, Ohio, October 1978.

Stacey, F. D., Physics of the Earth, 2nd ed.: John Wiley and Sons, New York, 1977.

Stauder, W., Tensional character of earthquake foci beneath the Aleutian Trench with relation to sea floor spreading: J. Geophys. Res. 73, 7693-7702, 1968.

Stein, S., and E. A. Okal, Seismicity and tectonics of the Ninetyeast Ridge area: evidence for internal deformation of the Indian plate: J. Geophys. Res. 83, 2233-2245, 1978.

Stolz, A., Changes in the position of the geocenter due to seasonal variations in air mass and ground water: Geophys. J. Roy. Astron. Soc. 44, 19-26, 1976.

Stolz, A., and nine others, Earth rotation measured by lunar laser ranging: Science 193, 997-999, 1976.

Sykes, L. R., Mechanisms of earthquakes and the nature of faulting on the mid-ocean ridges: J. Geophys. Res. 72, 2131-2153, 1967.

Tapponier, P., and Molnar, P., Active faulting and tectonics in China: J. Geophys. Res. 82, 2905-2930, 1977.

Thatcher, W., and J. B. Rundle, A model for the earthquake cycle in underthrust zones: J. Geophys. Res. 84 (in press), 1979.

US Geological Survey, Office of Earthquake Studies, Five-Year Plan for Earthquake Prediction (1980-84): US Geological Survey, Reston, Virginia, 1979.

Van Flandern, T. C., A determination of the rate of change of G: Mon. Not. Roy. Astron. Soc. 170, 333-342, 1975.

Vogel, A., Terrestrial and space techniques in earthquake prediction research: Proceedings of the Seminar on Earthquake Prediction Research, European Space Agency Report SP-149, April 1979.

Walcott, R. I., Present tectonics and late Cenozoic evolution of New Zealand: Geophys. J. Roy. Astron. Soc. 52, 137-164, 1978a.

Walcott, R. I., Geodetic strains and large earthquakes in the Axial Tectonic Belt of North Island, New Zealand: J. Geophys. Res. 83, 4419-4430, 1978b.

Wallace, R. E., Goals, strategy, and tasks of the Earthquake Hazard Reduction Program: U. S. Geological Survey Circular 701, 1974.

Wang, C. Y., Some aspects of the Tangshan (China) earthquake of 1976: unpublished manuscript, 1978.

Warburton, R. J., and J. M. Goodkind, Detailed gravity-tide spectrum between one and four cycles per day: Geophys. J. Roy Astron. Soc. 52, 117-136, 1978.

Watts, A. G., J. K. Weissel, and F. J. Davey, Tectonic evolution of the South Fiji marginal basin, in Island Arcs, Deep-Sea Trenches, and Back-Arc Basins, ed. M. Talwani and W. C. Pitman, III: Amer. Geophys. Union, Washington, D. C., 1977.

Weissel, J. K., Evolution of the Lau Basin for growth of small plates, in Island Arcs, Deep-Sea Trenches, and Back-Arc Basins, ed. M. Talwani and W. C. Pitman, III: Am. Geophys. Union, Washington, D. C., 1977.

Whitcomb, J. H., Impact of technology on tectonophysics, in Impact of Technology on Geophysics: National Academy of Sciences, Washington, D. C., 1978.

Whitcomb, J. H., J. D. Garmany, and D. L. Anderson, Earthquake prediction: variation of seismic velocities before the San Fernando Earthquake: Science 180, 632-635, 1973.

Williams, J. G., Present scientific achievements from lunar laser ranging, in Scientific Applications of Lunar Laser Ranging, ed. J. D. Mulholland, Reidel, Dordrecht, 1977.

Williams, J. G., M. A. Slade, D. H. Eckhardt, and W. M. Kaula, Lunar physical librations and laser ranging: The Moon 8, 469-483, 1973.

Williams, J. G., and sixteen others, New test of the principle of equivalence from lunar laser ranging: Phys. Rev. Lett. 36, 451-554, 1976.

Williams, J. G., W. S. Sinclair, and C. F. Yoder, Tidal acceleration of the Moon: Geophys. Res. Lett. 5, 943-945, 1978.

Wilson, C. R. and R. A. Haubrich, Earthquakes, weather, and wobble: Geophys. Res. Lett. 4, 283-284, 1977.

Wyss, M., The appearance rate of premonitory uplift: Bull. Seis. Soc. Amer. 67, 1091-1098, 1977.

York, J. E., R. Cardwell, and J. Ni, Seismicity and Quaternary faulting in China: Bull. Seis. Soc. Amer. 66, 1983-2001, 1976.

INDEX OF PEOPLE

INDEX OF PLACES

INDEX OF THINGS

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16. Abstract

In cooperation with other Federal government agencies, and the governments of other countries, NASA is undertaking a program of research in geodynamics. This document describes the present program activities and plans for extension of these activities in the time period 1979-1985. The program includes operation of observatories for laser ranging to the Moon and to artificial satellites, and radio observatories for very long baseline microwave interferometry (VLBI). These observatories are used to measure polar motion, earth rotation, and tectonic plate movement, and serve as base stations for mobile facilities. The mobile laser ranging and VLBI facilities are used to measure crustal deformation in tectonically active areas.

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